FLUME STUDY ON

SALINITY INTRUSION IN ESTUARIES

SYSTEMATIC INVESTIGATION VARIATION
BOUNDARY CONDITIONS AND FLOW REGIME

AFGEHANDELD

DELF HYDRAULICS LABORATORY
M 896-X
FLUME STUDY ON
SALINITY INTRUSION IN ESTUARIES

(English version)

Systematic Investigation Variations in
Boundary Conditions and Flow Regime

M 896 - X
November 1970
CONTENTS

COMPOSITION OF THE REPORT
SUMMARY
LIST OF FIGURES
NOTATIONS

1. INTRODUCTION 1.
2. BRIEF REVIEW OF THE STUDY 2.
3. EXPLANATION OF THE RESULTS 3.
**COMPOSITION OF THE REPORT**

The full Report consists of 57 parts. Part 1 is an outline of the study, while Parts 2 upto and including 57 give the experimental results. The library version of the Report consists of Parts 1 (outline) and 9 (test T 145).

**COMPONENT PARTS OF THE FULL REPORT**

<table>
<thead>
<tr>
<th>Part</th>
<th>Subject</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Outline experimental study</td>
</tr>
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<td>21,22</td>
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<td>Tests variation fresh water discharge</td>
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<td>29,30</td>
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<td>tests T34B, T34C (also codified as T34, T35)</td>
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<td>43,44,45,46,47</td>
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<td>48,49,50,51,52</td>
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<td>53,54,55,56,57</td>
<td>Tests variation condition sea basin</td>
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SUMMARY

To get an insight into the salinity intrusion in the Rotterdam Waterway fundamental research has been executed with density currents in a tidal flume. In the scope of the flume study a systematic investigation was carried out in which the boundary conditions and the flow conditions were varied within a wide range. The effect of the variations on the salinity intrusion and the flow pattern was studied. The qualitative aspects (tendencies) may be applied for practice (Rotterdam Waterway), but the quantitative data have been evaluated for fundamental research. A two-dimensional analysis has been made to get an insight for a physical interpretation of the phenomenon, and a one-dimensional analysis to get an insight into the coefficients for an operational computing program for nonhomogeneous tidal computations. By means of a data processing system, a large number of data were generated as computer output (printed output and plotted graphs).
LIST OF FIGURES

1. Rotterdam Waterway Estuary
2. Set-up of the flume study
3. Scheme experimental set-up
4. Test systematic investigation
5. Scheme two-dimensional analysis
6. Scheme one-dimensional analysis
7. Outline computer output
8. Salinity intrusion versus water height
9. Salinity intrusion versus flume length
10. Salinity intrusion versus fresh water discharge
11. Salinity intrusion versus tidal difference
12. Salinity intrusion versus salt concentration sea
13. Salinity intrusion versus roughness
14. Salinity intrusion versus air injection in flume
15. Salinity intrusion versus condition of sea
16. Effect type of roughness on salinity intrusion
17. Effect air injection with variable water height
18. Effect air injection with variable fresh water discharge
19. Typical results two-dimensional analysis
20. Typical results one-dimensional analysis
NOTATIONS

\( c \) : salt concentration
\( \bar{c} \) : salt concentration, cross-sectional mean value
\( c_s \) : salt concentration (constant) on sea boundary
\( g \) : gravitational acceleration
\( h \) : water height
\( h-h_o \) : water height, referring to mean sea level
\( h_s \) : water height sea boundary (boundary condition)
\( p \) : pressure
\( t \) : time
\( u \) : velocity component in \( x \)-direction
\( \bar{u} \) : velocity component, cross-sectional mean value
\( u_x \) : shear velocity according \( u_x^2 = \tau/\rho \)
\( u_{xb} \) : shear velocity at the bottom according \( u_{xb}^2 = \tau_b/\rho \)
\( v \) : velocity component in \( y \)-direction
\( x \) : horizontal coordinate
\( y \) : vertical coordinate

C : resistance coefficient according to Chézy
\( D_x \) : diffusion coefficient for the \( x \)-direction
\( D_y \) : diffusion coefficient for the \( y \)-direction
\( D_x' \) : dispersion coefficient
\( Fr \) : Froude number
\( Fr' \) : densimetric Froude number
\( Ke \) : Keulegan number
\( K_y \) : eddy viscosity
\( L \) : equivalent length
\( L_m \) : material flume length
\( Q \) : discharge
\( Q_L \) : constant discharge (boundary condition)
NOTATIONS (continuation)

R  : hydraulic radius
Re : Reynolds number
Hi : Richardson number
Rp : pressure ratio
T  : tidal period
Tx : diffusive transport in x-direction
Ty : diffusive transport in y-direction
Tx' : dispersive transport

MVS (M): maximum flood current
HMK (H): high water slack
ME (L): maximum ebb current
LMK (L): low water slack

λ  : length tidal wave according to $\lambda = \sqrt{gh_o} T$
ν  : kinematic viscosity
ρ  : density
$\bar{\rho}$ : density, cross-sectional mean value
τ  : shear stress
τb : shear stress at the bottom
1. **INTRODUCTION**

By letter No. 6698, of August 10, 1966, the Delta Service of the Rijkswaterstaat (Government Department of Transport and Waterways) commissioned the Delft Hydraulics Laboratory to carry out model research on density currents in a tidal flume. This research, which has a fundamental character, is guided on behalf of the sponsor by Dr. J.J. Dronkers, Director of the Hydraulics Department of the Delta Service.

Within the scope of a long-term framework a systematic investigation has been carried out for background information to get an insight into the salinity intrusion in the Rotterdam Waterway Estuary. In the tidal flume the boundary conditions and the flow conditions were varied over a wide range and the effect of the variations on the salinity intrusion and the flow pattern was studied. The results give tendencies which are applicable for the Rotterdam Waterway (qualitative aspects), but they may not be applied quantitatively because of the schematic character of the flume study.

The data have been evaluated for fundamental research. Within the framework of both a two-dimensional and a one-dimensional analysis attempts are made to find a correlation between the shear stress and salt transport on the one hand, and parameters which characterize the salinity and flow condition on the other hand. The long-term objective is to have an operational mathematical model for prediction of the salinity intrusion in an estuary based on results (physical correlations) of the flume study.

There have been 56 runs the results of which have been collected in Parts 2 to 57 of this Report. The measurements were made from December 1968 up to December 1969, and data processing was finished in November 1970. The work was carried out under the supervision of A.J. van Rees, who also drew up this Report.
2. BRIEF REVIEW OF THE STUDY

The prototype, the Rotterdam Waterway Estuary, is given in Figure 1, and the set-up of the flume study is shown in Figure 2. The tidal flume is a schematic representation of the prototype on a scale 1 : 64 in a vertical direction and a scale 1 : 640 in a horizontal direction (scales within a certain range arbitrarily adjustable). The flume was 0.50 m deep, 0.67 m wide and 100 m long. It was connected with a rectangular basin (schematized sea) with a continuously adjustable water level and a constant salt concentration. At the end of the flume a continuously adjustable discharge and a constant (fresh water) discharge could be controlled. The tidal flume was constructed in such a way (smooth walls and sufficiently wide) that a two-dimensional flow could be expected.

A general view of the tidal flume and the measuring equipment is given in Figure 3. For a detailed description of the set-up of the flume study reference is made to Report M 896 - 1, for the constructive aspects to Report M 896 - 2, and for the set-up of the measuring programme and the measuring technique to Report M 896 - 4, all of which are in preparation.

A summary of the tests of the systematic investigation is given in Figure 4. In each of the series of measurements one of the determining conditions was varied, while the other conditions were kept constant. The data have been used for a two-dimensional analysis (scheme in Figure 5) for the purpose of a physical interpretation, while to get an insight into the coefficients for non-homogeneous tidal computations (DHL publication No. 52) a one-dimensional analysis was performed (scheme in Figure 6). The results are available as printed output and plotted graphs, an outline of which is found in Figure 7. For the set-up of the numerical processing, reference is made to Report M 896 - 5, now in preparation.
3. **EXPLANATION OF THE RESULTS**

A sensitive parameter which roughly characterizes the salinity distribution is the intrusion-length. On the basis of this parameter in executing the programme the tests were selected to cover the phenomenon in a sufficiently wide range. Figures 8 up to and including 15 give an impression for runs respectively with variation of water depth, flume length, fresh water discharge, tidal difference (double the amplitude), salt concentration of the sea, roughness, air injection and testing the sea boundary. Figures 16 and 17 show the effect of the type of roughness elements and the effect of air injection together with variation of water height. Figure 18 shows the effect of air injection together with variation of fresh water discharge. The graphs of Figure 8 up to and including Figure 18 are given for a rough characterization of the tests of the systematic study.

An example of the results of the two-dimensional analysis has been given in Figure 19 and similarly the one-dimensional analysis in Figure 20. This concerns results for the mass transfer (salt), while for the transfer of impulse a similar presentation is given in the various parts of this Report. For the physical interpretation of the two-dimensional model Report M 896 - 11 is in preparation and Report M 896 - 12 for the one-dimensional case.

The results of the 56 runs are available as computer-output, tables and plots. All available data is in the tables; the plots are restricted to the characteristic aspects. As an example of the plots Part 9 (run T 145) has been chosen. Apart from a different type of roughness, this concerns a run similar to the reference run.
SCHEMATIZATION PROTOTYPE PROBLEM

SCHEMATIZATION TO TWO-DIMENSIONAL NON-HOMOGENEOUS TIDAL FLOW

\[ h = f(x,t) \]
\[ u = f(x,y,t) \]
\[ v = f(x,y,t) \]
\[ \rho = f(x,y,t) \]

TIDAL MODEL OF SCHEMATIZED ESTUARY

CONTINUOUS CONTROL OF SEA BOUNDARY:
- \( h_b \): WATER LEVEL
- \( c_s \): SALT CONCENTRATION

FLUME:
- ADJUSTABLE ROUGHNESS
- ADJUSTABLE MIXING

CONTROL OF RIVER BOUNDARY:
- \( q_f \): FRESH WATER DISCHARGE
- \( q_t \): CONTINUOUS CONTROL OF FLOW

SAMPLING SYSTEM

MEASUREMENT OF:
- \( h \): WATER LEVEL
- \( u \): HORIZONTAL VELOCITY
- \( \rho \): DENSITY

SAMPLING INTERVALS:
- \( \Delta x = 3.65m \) (2340m PROTOTYPE)
- \( \Delta y = 0.077h_0 \) (ABOUT 1m PROTOTYPE)
- \( \Delta t = 0.04T \) (ABOUT 1/2 HOUR PROTOTYPE)

DATA PROCESSING SYSTEM

GENERAL SET-UP OF TIDAL FLUME INVESTIGATION

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M. 896 - 1391 FIG. 2
SET-UP OF THE TIDAL SALINITY FLUME

SET-UP MEASURING DEVICES

SCHEME EXPERIMENTAL SET-UP

DELFt HYDRAULICS LABORATORY
<table>
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<tr>
<th>RUN NO.</th>
<th>UNITS</th>
<th>MODEL</th>
<th>PROTOTYPE</th>
<th>DETAILS</th>
<th>RUN NO.</th>
<th>UNITS</th>
<th>MODEL</th>
<th>PROTOTYPE</th>
<th>DETAILS</th>
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<td>m</td>
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<td>-1899</td>
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<td>118</td>
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<td>-0.00145</td>
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<tr>
<td>120</td>
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<td>-0.00181</td>
<td>-593</td>
<td>AIR 80 cc/m²/s</td>
<td>124</td>
<td>40</td>
<td>125</td>
<td>cc = 10⁶ m³</td>
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<tr>
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**DATA REFERENCE TESTS T3/T3B**

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<th>UNITS</th>
<th>MODEL</th>
<th>PROTOTYPE</th>
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<tbody>
<tr>
<td>1° WATER HEIGHT</td>
<td>m</td>
<td>0.216</td>
<td>13.8</td>
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<td>30</td>
</tr>
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<td>8° CONDITION SEA</td>
<td>NO AIR</td>
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**SCALE FACTORS**

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<th>HEIGHT</th>
<th>LENGTH</th>
<th>VELOCITY</th>
<th>TIME</th>
<th>DISCHARGE</th>
<th>SALT CONC.</th>
<th>ROUGHNESS</th>
<th>AIR DISCHARGE</th>
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<td>0.57</td>
<td>327680</td>
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<td>0.640</td>
<td>0.6</td>
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<td>1</td>
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<td>327680</td>
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<td>0.6</td>
<td>0.6</td>
<td>0.80</td>
<td>327680</td>
<td>1</td>
<td>0.57</td>
<td>327680</td>
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<tr>
<td>4° TIDAL DIFFERENCE</td>
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<td>0.6</td>
<td>0.6</td>
<td>0.80</td>
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<td>1</td>
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<td>5° SALT CONC. SEA</td>
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<td>0.6</td>
<td>0.80</td>
<td>327680</td>
<td>1</td>
<td>0.57</td>
<td>327680</td>
</tr>
<tr>
<td>6° ROUGHNESS FLUME</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.80</td>
<td>327680</td>
<td>1</td>
<td>0.57</td>
<td>327680</td>
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<td>7° AIR INJECTION</td>
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<td>8° CONDITION SEA</td>
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<td></td>
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**TESTS SYSTEMATIC INVESTIGATION**

DELFT HYDRAULICS LABORATORY

M.896-1395 FIG. 4
Basic equations:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]

\[
\frac{\partial c}{\partial t} + \frac{\partial c}{\partial x} + \frac{\partial c}{\partial y} + \frac{\partial T_x}{\partial x} \frac{\partial T_x}{\partial y} + \frac{\partial T_y}{\partial x} \frac{\partial T_y}{\partial y} = 0
\]

\[
\rho \left( \frac{\partial v}{\partial t} + \frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} \right) + \frac{\partial p}{\partial y} - \frac{\partial x}{\partial x} + \rho g = 0
\]

\[
\rho \left( \frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} \right) + \frac{\partial p}{\partial x} - \frac{\partial x}{\partial y} = 0
\]

Input data:

- \( h = f(x, t) \): water height
- \( u = f(x, y, t) \): horizontal velocity
- \( \rho = f(x, y, t) \): density

Suppositions:

1. \( \frac{\partial T_x}{\partial x} \ll \frac{\partial T_y}{\partial y} \) and \( \frac{\partial x}{\partial x} \ll \rho g \)

2. \( T_y = -D \frac{\partial c}{\partial y} \) and \( \frac{\partial c}{\partial y} = \frac{\partial c}{\partial y} (\rho K \frac{\partial u}{\partial y}) \)

Boundary conditions:

- \( v = 0 \) for \( y = 0 \)
- \( p = 0 \) for \( y = h \)
- \( T_y = 0 \)
- \( \tau = 0 \)

Analysis:

\[
v = -\int_0^h \frac{\partial u}{\partial x} \, dy
\]

\[
D_y = -\frac{\partial c}{\partial y} \left( \frac{\partial c}{\partial x} + \frac{\partial c}{\partial y} \right) \, dy
\]

\[
\frac{\partial p}{\partial x} = -\int_y^h \frac{\partial}{\partial x} \left( \frac{\partial p}{\partial y} \right) \, dy - \left( \frac{\partial h}{\partial x} \right) \frac{\partial h}{\partial x}, \text{ in which}
\]

\[
\frac{\partial h}{\partial y} = -\{ \rho \left( \frac{\partial v}{\partial t} + \frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} \right) + \rho g \}
\]

\[
K_y = \frac{1}{\rho \frac{\partial u}{\partial y}}, \text{ because } K_y = \frac{1}{\rho \frac{\partial u}{\partial y}}
\]

Significant parameters:

\[
R_i = \frac{-\frac{\partial h}{\partial y}}{\rho \left( \frac{\partial u}{\partial y} \right)^2} \text{ (Richardson number), } u_* = \frac{\tau}{11 \rho} \text{ (shear velocity)}
\]

SCHEME TWO-DIMENSIONAL ANALYSIS

DELFT HYDRAULICS LABORATORY

M.896 - 1397 FIG. 5
Basic equations:

\[
\frac{\partial (hu)}{\partial x} + \frac{\partial h}{\partial t} = 0
\]

\[
\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + \frac{1}{\rho} \frac{\partial (T^* h)}{\partial x} = 0
\]

\[
\rho \left( \frac{\partial \bar{u}}{\partial t} + u \frac{\partial \bar{u}}{\partial x} \right) + \frac{\partial \bar{P}}{\partial x} + \frac{\tau_b}{\bar{\rho}} = 0
\]

Input data:

\[
h = f(x, t) : \text{water height}
\]

\[
\bar{u} = f(x, t) : \text{horizontal velocity}
\]

\[
\bar{\rho} = f(x, t) : \text{density}
\]

Suppositions:

\[
T_x^* = -D_x^* \frac{\partial \bar{c}}{\partial x} \quad \text{and} \quad \tau_b = \frac{\tau_{bl}}{c^2} \cdot \bar{\rho} \bar{u} |\bar{u}|
\]

Boundary condition:

For \( x = x_{in} (\text{fresh water section}) \):

\( T_x^* = 0 \)

Rate of pressure:

\[
\frac{\partial \bar{P}}{\partial x} = \frac{1}{2} gh \cdot \frac{2 \bar{u}}{\partial x} + \bar{\rho} \frac{\partial \bar{h}}{\partial x}
\]

Analysis:

\[
D_x^* = \frac{1}{h} \int_{x_{in}}^{x} h \left\{ \frac{\partial \bar{c}}{\partial t} + u \frac{\partial \bar{c}}{\partial x} \right\} \, dx
\]

\[
D_x^* = \frac{\partial \bar{c}}{\partial x} - \frac{\partial \bar{c}}{\partial x}
\]

\[
\bar{c} = \frac{\partial}{\partial x} \left\{ \frac{\bar{\rho} (\bar{u} + u) (\frac{\partial \bar{c}}{\partial x}) + \bar{P}}{\bar{\rho} \bar{u} |\bar{u}|} \right\}
\]

\[
\frac{\tau_b}{c^2} = \frac{\tau_{bl}}{\bar{\rho} \bar{u} |\bar{u}|}
\]

Significant parameters:

\[
Re = \frac{\bar{u} h}{v} \quad \text{(Reynolds number)}, \quad Ke = \frac{3}{\bar{u}} \quad \text{(Keulegan number)}
\]

\[
Fr = \frac{\bar{u}^2}{gh} \quad \text{(Froude number)}, \quad Fr = \frac{\bar{u}^2}{\sqrt{\bar{P}}} \quad \text{(Froude number)}
\]

\[
P_p^{-1} = \frac{\bar{P}}{\frac{\partial \bar{h}}{\partial x}} \quad \text{(pressure ratio)}, \quad u_{*b} = \frac{\tau_b}{|\tau_{bl}|} \sqrt{\frac{|\tau_{bl}|}{\bar{\rho}}} \quad \text{(shear velocity)}
\]

**SCHEME ONE-DIMENSIONAL ANALYSIS**

_Delft Hydraulics Laboratory_  
M.896-1399 FIG. 6
### OUTPUT TWO-DIMENSIONAL ANALYSIS

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<tr>
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<td>( u )</td>
<td>( U )</td>
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<tr>
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</tr>
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<td>( C )</td>
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### OUTPUT ONE-DIMENSIONAL ANALYSIS

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<th>Quantity</th>
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<tr>
<td>12</td>
<td>( \frac{\partial v}{\partial z} )</td>
<td>( \frac{\partial v}{\partial z} )</td>
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</table>
SALINITY INTRUSION VERSUS FLUME LENGTH

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M.896–1405  FIG. 9
SALINITY INTRUSION VERSUS SALT CONCENTRATION SEA

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M.896-1411 FIG.12

EXPERIMENTAL DATA
REFERENCE TEST
A4
CONDITION SEA BASIN:
- SKIMMER REMOVED
- NO WITHDRAWAL OF FRESH WATER
- AIR INJECTION $80 \times 10^{-5} \text{ m}^3/\text{m}^2\text{s}$
- CIRCULATION FLOW MINIMUM

SALINITY INTRUSION VERSUS CONDITION SEA

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EFFECT TYPE OF ROUGHNESS ON SALINITY INTRUSION

VERTICAL PLATES ON THE BOTTOM

VERTICAL BARS COVERING THE WHOLE DEPTH

WATER HEIGHT (m)

SALINITY INTRUSION (m)

EXPERIMENTAL DATA
REFERENCE TEST

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M.896-1419 FIG. 16
EFFECT AIR INJECTION WITH VARIABLE WATER HEIGHT

INJECTION OF AIR
5.10^{-5} m^3/m^2 s

NO AIR

WATER HEIGHT (m)

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M.896-1421 FIG. 17
EFFECT AIR INJECTION WITH VARIABLE FRESH WATER DISCHARGE

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M.896-1423 FIG. 18