PHYSICAL MODELING OF SALINITY INTRUSION INTO ROTTERDAM WATERWAY ESTUARY

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Abstract

Reproducing vertical mixing due to bed-shear generated turbulence is a critical issue in physical salinity intrusion modeling for partly mixed estuaries. It involves the selection of a type of added resistance, which acts properly at a mixing device. Within this context, the paper summarizes experimental evidence, obtained in the Rotterdam Waterway salinity intrusion model, which shows that (1) to some extent the vertical salinity distribution can be influenced by the type of added resistance, and (2) using the type of resistance selected for this model, salinity is properly reproduced for a range of conditions.

1. Introduction

In the 1976 volume of Annual Review of Fluid Mechanics, Fischer (1976) concludes that hydraulic scale models, so long as their restrictions are borne in mind, are useful tools for problems of salinity intrusion, involving three-dimensionality, complex boundaries or stratification, for which hardly any other tools are available. With respect to the reproduction of the vertical salinity distribution in partly mixed models, he notes that vertical resistance strips play an empirically important role, but their role is by no means clear. Harleman (1971) gives scaling relationships for these models, elaborating upon the role of the strips as an empirical factor. Simmons and Bobb (1965) report an excellent reproduction of salinity distribution by means of the strips for the Hudson River model ($n = 10$).

Within this context the paper gives a short description of the processes, which influence the salinity intrusion into the partly mixed Rotterdam Waterway Estuary. It shows that reproduction of the large-scale processes is straightforward, while vertical small-scale mixing is insufficient unless compensated by added resistance acting as a mixing device. It presents experiments on the effect of the type of added resistance on the salinity distribution, and describes the type of added resistance used in the Rotterdam Waterway salinity intrusion model. It summarizes model-prototype comparisons, which show this type of added resistance to reproduce the salinity intrusion properly over a range of tidal conditions and fresh water discharges.

2. Rotterdam Waterway Estuary

The Rotterdam Waterway Estuary (Fig. 1), is formed by the New Meuse, the Old Meuse and the New Waterway. Fresh water, which flows into the estuary through the New Meuse and the Old Meuse, issues into the North Sea through the New Waterway.

On a large scale, salinity intrusion into the partly mixed estuary depends on tidal action and fresh water discharge. Gravitational circulation is a driving mechanism. Large-scale mixing is induced by phase differences between the tidal velocities in the New Meuse and the Old Meuse. It further is due to density induced exchange flows between the main estuary channels and harbor basins located along the estuary (Abraham et al, 1986). These large-scale processes act by advection.

Small-scale turbulent processes influence the stratification and thereby the strength of the gravitational circulation. They are due to bed-shear generated turbulence and turbulence generated by side walls and the groynes at the banks of the New Waterway.

3. Rotterdam Waterway salinity intrusion model

The salinity intrusion in the Rotterdam Waterway has been studied in a physical model (vertical length scale 1/64, horizontal length scale 1/640, distortion 10). In 1965 the model was built for a navigability study. The first task of the model was to provide information on the three-dimensional flow field near the entrance of the Rotterdam Waterway and the effect of coastal and density currents thereon. A model-prototype comparison showed this flow field to be properly reproduced (Breusers and van Os, 1981). In a later stage, emphasis shifted gradually to determining the effect of changes in the geometry of the estuary on salinity intrusion. At present the model is no longer in use. It is being replaced by a three-dimensional mathematical model. This development is supported by a flume study and field experiments, such as the observation of internal wave activity in the Rotterdam Waterway Estuary by acoustic images (Pietrzak et al, 1989). To account for the damping of turbulence by density stratification, the conversion of turbulent energy into internal wave energy, and vice versa, will eventually be incorporated in the mathematical model (Uittenbogaard and Baron, 1989).

4. Scaling requirements

The model follows the Froude scaling law, $u_r^2 = h_r$, with $\rho_r = 1$ and therefore $S_r = 1$, where subscript r is the ratio of model-to-prototype quantity, u is a longitudinal velocity, h is a vertical length, ρ is the density and S is the salinity. The model reproduces the above large scale processes correctly, once it is adjusted for tidal propagation.

Distortion implies $I_r = h_r/L_r = n$, where I is the slope of the water surface, L is a horizontal length and n is the distortion. The effect of the bottom shear stress, τ_b, on the surface slope is given by $\tau_b/\rho h$, that of the sidewall shear stress, τ_w, by $\tau_w/\rho b$, where h and b are the depth and width of the channel. Therefore, reproduction of tidal propagation requires

$$(\tau_b)_r = n\, h_r \qquad\qquad (\tau_w)_r = h_r \tag{1}$$

In accordance with Eq. 1, the required frictional resistance of the bed increases with the distortion and that of the side walls does not. Therefore, in a distorted model bottom roughness must be added, addition of side wall roughness is not needed and groynes and other protrusions from the side walls must be reproduced geometrically similarly. The distortion is not significant for this geometrically similar reproduction as the flow separates from the protrusion in nature.

Conservation of salinity implies that the vertical gradient of the vertical transport of salinity, F_z, must scale as the horizontal gradient of the longitudinal advective transport, uS. The turbulent energy balance requires the production of turbulent energy, P, to scale as F_z. Hence, since $S_r = 1$, proper reproduction of stratification requires

$$(F_z)_r = n\, h_r^{1/2} \qquad\qquad P_r = n\, h_r^{1/2} \tag{2}$$

In accordance with Eq. 2, the required mixing increases with the distortion. Therefore, after adjusting a distorted model for tidal propagation, the salinity distribution must be verified.

For side wall generated turbulence, eddy viscosity and eddy diffusivity are propositional to $(\tau_w/\rho)^{1/2}b$. This implies that the requirements of Eqs. 1 and 2 are compatible. Mixing due to side wall roughness generated turbulence is correctly reproduced in a distorted model, once its effect on tidal propagation is properly reproduced. The same holds for mixing due to groynes and other protrusions from the side walls, the shape of which is reproduced geometrically similar.

For bed-shear generated turbulence eddy viscosity and eddy diffusivity are proportional to $(\tau_b/\rho)^{1/2}h$. Assuming that after adjustment for tidal propagation this also holds for a distorted model, the production of turbulent energy is too much concentrated at the bottom, the vertical mixing is $n^{1/2}$ times too small, and the horizontal exchange is $n^{3/2}$ times too strong. This means that the additional frictional resistance must be provided by resistance elements, which act properly as a vertical mixing device. The strips mentioned in the introduction, which distribute the generation of turbulence over the depth and induce vertical currents along their faces, are introduced as such. While reinforcing the vertical mixing, the resistance elements are likely to reinforce the horizontal exchange as well.

5. Effect of type of resistance on salinity

Additional resistance elements - all with the same effective resistance - were compared with respect to their effect on salinity distribution: cubes ($5 \times 5 \times 5$ cm^3) placed on the bottom, vertical bars (horizontal cross-section $\frac{1}{2} \times \frac{1}{2}$ cm^2) over the whole depth, and elements with a cross-shaped horizontal cross-section (two vanes, 3×3 cm^2 each) (Fig. 2). The experiments were made in a flume, schematizing the Rotterdam Waterway Estuary as a single straight channel with constant rectangular cross-section without harbor basins along it at the same scale as the Rotterdam Waterway salinity intrusion model. The flume width-to-depth ratio was 3. It was about equal to that of the New Waterway section of the distorted model. The corresponding prototype value is ten times larger as a result of the model distortion.

Fig. 3 gives results of the experiments. For the flume experiments, the total resistance (of bottom and side walls combined) corresponded to that of the Rotterdam Waterway at model scales. For some of the flume experiments, the contribution of the side walls was about 10% (Fig. 3a), for other flume experiments (Fig. 3b) it was about 30% as for the Rotterdam Waterway salinity intrusion model (Fig. 3c) because of the groynes. Fig. 3 shows the effect of the type of additional resistance to decrease with increasing side wall resistance. From this perspective, relatively wide estuaries are more difficult to be modeled than relatively narrow estuaries.

Because of the large-scale mixing processes and the side-wall effects, the type of additional resistance was not deemed critical for Rotterdam Waterway conditions. The cross-shaped elements were finally selected for practical modeling reasons: They allowed easy cleaning of the model. Their resistance did not vary significantly with the direction of flow in the horizontal plane. They would cause little accumulation of bed material, simulating sediment transport.

6. Model-prototype comparisons

After the model was adjusted for tidal propogation, using the cross-shaped elements, model-prototype comparisons were made for verification of the velocity and salinity distribution. Table 1 gives the conditions involved for the comparisons given in this paper, in addition to those given by Breusers and van Os (1981). It lists: the fresh water discharge of the New Waterway (Q), the tidal range at the mouth of the estuary (Δh) and the estuary number, E_D, a measure of the stratification (Thatcher and Harleman, 1981), defined as

$$E_D = \frac{P_t}{Q\ T} \quad \frac{u_o^2}{\frac{\Delta\rho}{\rho}\ g\ h_0} \tag{3}$$

where $\Delta\rho$ is the difference in density between river and sea water, P_t is the volume of sea water entering the estuary on the flood tide, T the duration of the tidal cycle, u_o is the maximum profile averaged flood velocity at the mouth of the estuary, h_o is the time averaged depth at the mouth of the estuary and g is the gravitational acceleration.

For the 1979 measurements listed in Table 1, velocity and density distributions were obtained from field measurements made from vessels at the centre line of the channels. For the 1976 period field data were obtained from a limited number of continuous density registrations from the banks. Wind influence was insignificant for the 1979 measurements. The E_D values listed in Table 1 refer to partly mixed conditions. They cover the range of stratifications of interest.

Fig. 4 gives the model-prototype comparisons for the 1979 periods, for $E_D = 2.2$ and $E_D = 0.62$. Fig. 4 is representative for the model-prototype agreement found. For September 17, 1979 with a neap-tide ($E_D = 0.37$) and wind set-up at sea noticeable deviations were found (Van der Heyden et al, 1984).

Fig. 5 gives the model-prototype comparison for August 1976, when river discharge was low, E_D ranging from 0.56 to 3.2. Fig. 5a gives the tidal conditions at the mouth of the estuary. Fig. 5b illustrates that in the vicinity of critical intakes, a proper reproduction of the duration of the periods with salinities above that of river water was found. As the measurements involved were made from the banks, differences in salinities were to be expected.

Summarizing, the Rotterdam Waterway Estuary being relatively narrow (Section 5), satisfactory model-prototype agreement was found for the range of stratifications of interest ($0.6 < E_D < 3.2$).

Table 1 Conditions for model-prototype comparisons

date	Q m^3/s	Δh m	E_D
21 May 1979	1690	1.63	0.62
10 Sept. 1979	880	2.00	2.2
20 Aug. 1976	784	1.22	0.56
27 Aug. 1976	736	2.14	3.2

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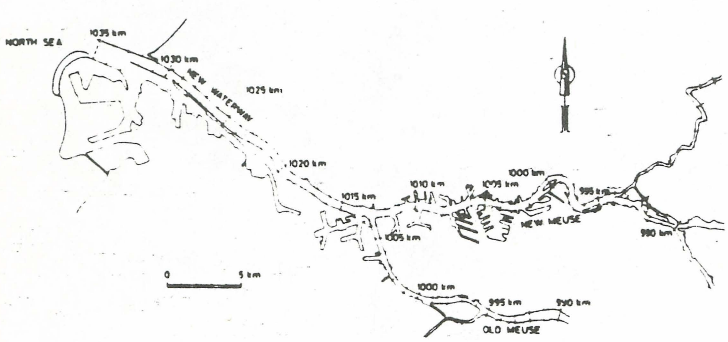

FIG 1. ROTTERDAM WATERWAY ESTUARY

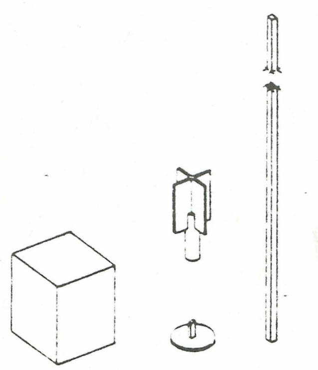

FIG 2. RESISTANCE ELEMENTS

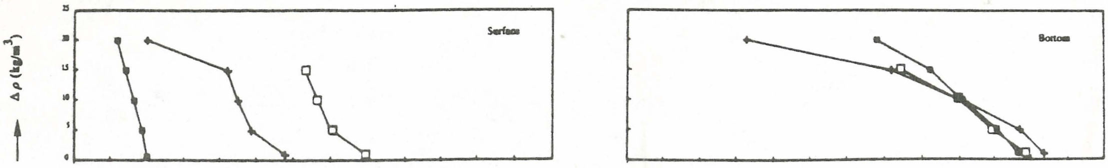

Fig3[a]. Tidal flume without side wall roughness ■T 3 (bars) +T 31 (cross shaped el.) □T 644 (cubes)

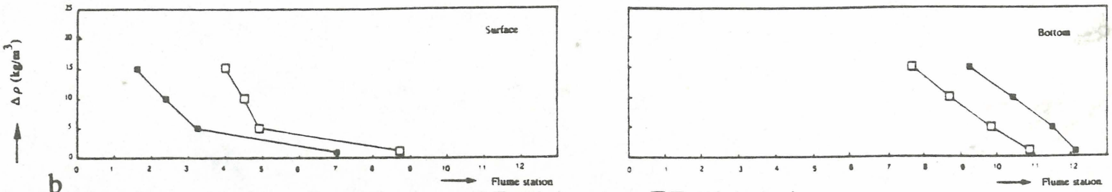

Fig 3[b]. Tidal flume with side wall roughness ■T 643 (bars) □T 640 (cubes)

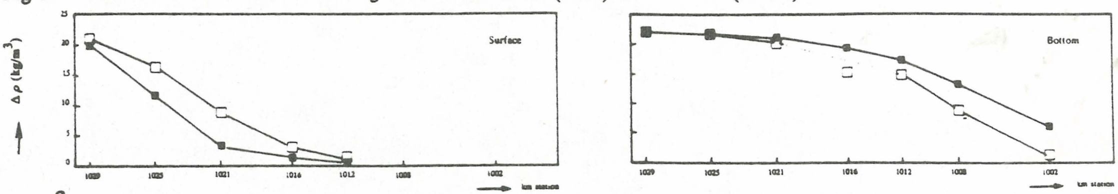

Fig 3[c]. Rotterdam Waterway Salt Intrusion Model ■T 41 (bars) □T 31 (cubes)

FIG 3. LONGITUDINAL DENSITY DISTRIBUTION AT HWS EFFECT OF TYPE OF RESISTANCE

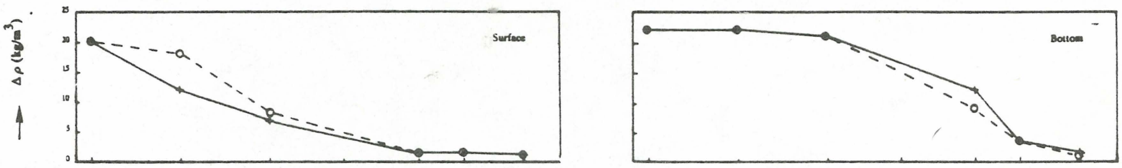

Fig 4[a]. 10 September 1979

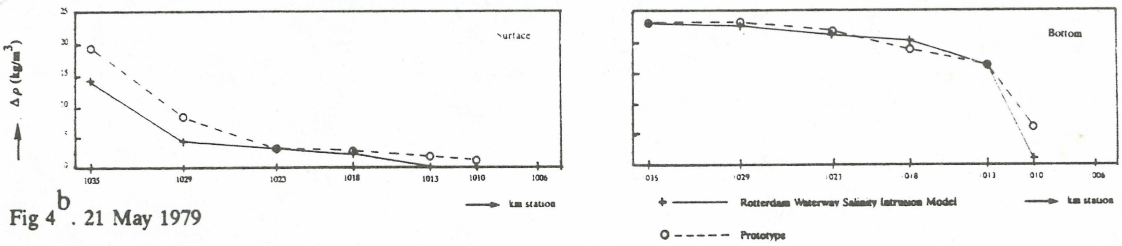

Fig 4[b]. 21 May 1979

FIG 4. LONGITUDINAL DENSITY DISTRIBUTION AT HWS MODEL-PROTOTYPE COMPARISON

Fig 5[a].
Tidal elevation
km station 1029

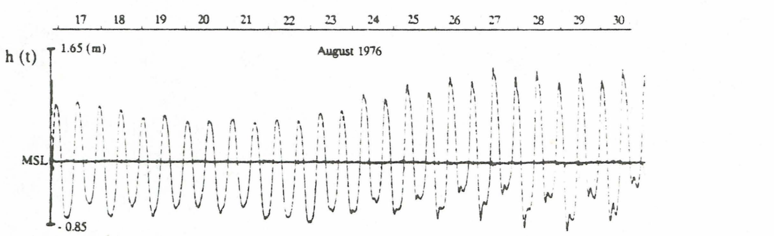

Fig 5[b].
Density response
Old Meuse
station 1003
1.0 m-MSL

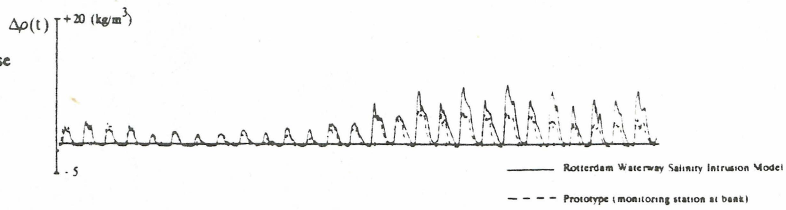

FIG 5. TIME SERIES MODEL-PROTOTYPE COMPARISON AUGUST 1976