NUMERICAL MODELLING OF SEAWATER PURGING IN HONG KONG SEA OUTFALL MODEL

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Abstract A previously developed numerical model for simulating sea water intrusion and purging process in sea outfalls is extended to be applicable to invert-connected systems and the calculated results are compared with the measurements with Hong Kong model outfall. The experiment observation shows that mechanism and process of purging sea water from invert-connected outfalls are very different from that from soffit-connected outfalls and these details can be well predicted by the numerical model.

Key words: numerical model; sea outfall; purging; intrusion; hydraulics.

INTRODUCTION

A large tunnelled sea outfall is envisaged to disposal sewage of Hong Kong into the sea. Diffuser of the outfall belongs to the invert-connected type according to the preliminary design. A scale model has been constructed to study seawater purging process for the outfall diffuser (Jong et al, 1994).

The problem of seawater intrusion into and purging from a sea outfall has drawn much attention. Many studies have been conducted in order to help solution of this problem (Charlton, 1982; Brooks, 1988; Wilkinson, 1984; Burrows et al, 1996). Early and small outfalls are mostly soffit-connected ones which riser offtakes are flush with the soffit of the outfall tunnel. Many fundamental studies focused on this type of outfalls (Wilkinson, 1984; Guo and Sharp, 1996; Burrows et al, 1996). While most of modern, large, deep tunnelled, sea outfalls are constructed in invert-connected type which riser offtakes are flush with the invert of the outfall tunnel. Though difference between soffit- and invert-connected outfall was noticed by some investigators (Charlton, 1985), also experiments with invert-connected, scale outfall models have been reported (Adams et al, 1994; Jong et al, 1994), no details of purging behaviours in invert-connected outfalls have been described.

It is usually believed that invert-connected outfalls can help to reduce purging discharge rate at which intruded seawater can be removed from the outfall, that is why this type of outfalls are designed. However, above conclusion cannot be reached by use of Munro head method since Munro head cannot tell essential difference between soffit- and invert-connected outfalls. Quantitative analysis may have to rely on numerical calculation. Again, previously developed numerical models mainly focused on soffit-connected outfalls (Larsen et al, 1992; Guo and Sharp, 1996). Therefore, a numerical model applicable to invert-connected outfalls is needed.

In the present study, observations and measurements have been conducted with the Hong Kong outfall model. Major attention has been paid to special characteristics of seawater purging in the case of invert connection. With the help of the observation, the numerical model developed by Guo and Sharp (1996) has been extended to be applicable to invert-connected outfalls and calibrated with the Hong Kong outfall model. Numerical modelling has been conducted to study details of seawater purging process in the model outfall. Since the model outfall is a scale model, results of numerical modelling can be directly translated into the prototype. It is hoped that the numerical model could supplement the shortage of the physical model. For instance, any possible geometrical modification of Hong Kong outfall in future can be readily taken into account by the numerical model.

NUMERICAL MODEL

The numerical model is an extended one from the model developed by Guo and Sharp (1996). Fig. 1 shows the grid system employed for flow calculation. For tunnel segments and risers with uniform cross sections, again, the following unsteady momentum equation (Eq. 1) is adopted, where Δ=density of fluid in each segment;

$$\varrho\frac{\partial V}{\partial t}+\frac{\partial P}{\partial x}+\left(\frac{\lambda}{8\psi}\right)\varrho\left|V\right|V=\varrho g\sin\theta \qquad (1)$$

V=average velocity on cross section; P=pressure; λ=friction factor; ψ= hydraulic radius=D/4 for a round pipe of diameter D or for a square pipe of hight

D, g=gravitational acceleration; x=distance along flow direction; t=time, and θ=angle of flow direction to the horizon. Using such grid system, sudden changes in tunnel cross section as Hong Kong outfall model is the case can be readily handled.

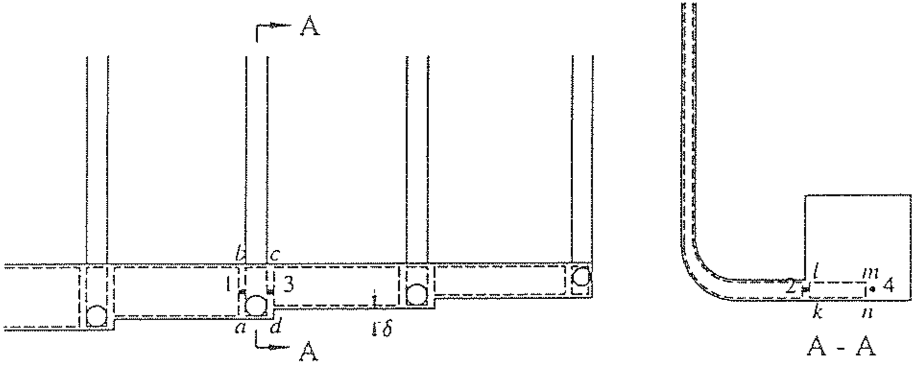

Figure 1: Outline of grid for flow calculation

For Tee junctions, as shown in Fig. 1, now momentum principle is applied to the control volume a-b-c-d for tunnel direction and the cylinder control volume k-l-m-n for riser offtake direction. It is obtained that

$$P_1-P_3=\left(\frac{A_3}{A_1}\right)\varrho_3|V_3|V_3-\varrho_1|V_1|V_1+\frac{\delta}{2}\varrho_3 g \quad (2)$$

and

$$P_1+P_3-2P_2=2\varrho_2|V_2|V_2-\left(2z+\frac{\delta}{2}\right)\varrho_3 g \quad (3)$$

where A=cross-section area; and subscripts indicate locations of the cross section; z=vertical distance between centre of the tunnel and centre of the riser offtake; δ=hight of the step in the tunnel. It has been assumed that

$$P_4=\frac{1}{2}\left(P_1+P_3+\frac{\delta}{2}\varrho_3 g\right) \quad (4)$$

Again, energy equation is employed to include head losses at bends and riser heads (Guo and Sharp, 1996). The continuity of flow at each tee, such as the example tee in Fig. 1, gives

$$Q_1-Q_2-Q_3=0 \quad (5)$$

where Q=discharge. Algorithm scheme for flow calculation is the same as used by Guo and Sharp (1996).

For salinity distribution calculation, the modified transport-dispersion equation is again used

$$\frac{\partial\varrho}{\partial t}+(V-kW)\frac{\partial\varrho}{\partial x}=\frac{E\partial^2\varrho}{\partial x^2} \quad (6)$$

Even for invert-connected outfalls, in many cases stratification also exists in the tunnel, therefore velocity of saline wedge, W, should again be considered with a modification coefficient k<1. For the dispersion coefficient, E,

$$E=aDu^*=mD\lambda^{0.5}V \quad (7)$$

Since friction velocity $u^*=(\lambda/8)^{0.5}$ has been adopted, $m=a/8^{0.5}$. Value of m will be discussed in next section.

For square cross section as Hong Kong outfall is the case, following the same procedure of deduction as was done by Guo and Sharp (1996), it is obtained that

$$W=\frac{D-h}{D}\left[(1+\sin\vartheta)2gh\frac{\varrho_s-\varrho_o}{\varrho_o}\right]^{0.5}-V \quad (8)$$

and

$$h=\frac{D(\varrho-\varrho_o)}{\varrho_s-\varrho_o} \quad (9)$$

where h=thickness of saline wedge in the tunnel.

INTRUSION AND PURGING IN INVERT-CONNECTED OUTFALL

Since numerical modelling aims at Hong Kong outfall model, observations and measurements are conducted with the model outfall and used to calibrate the numerical model.The model outfall is a 1:20 densimetric

Froude scale model originally designed for short term use by Delft Hydraulic Laboratory (Jong et al, 1994) and recently refurbished into a research facility. Diffuser tunnel of the model is 33.2m long, with a square cross section initially high 248mm and then tapering seaward. Soffit and also invert of the tunnel is sloping upward at approximately 1:500. Sixteen vertical risers of 8.75m high are connected to the invert of the tunnel (except the most seaward one), each riser having an internal diameter of 44mm and spaced at 1875mm apart. To reduce the length of the sea tank over the riser heads, the diffuser tunnel is turned through 180° at mid-length. Eight risers are connected in front of the turn and the rest eight behind. Length of the turn and transitions in front and behind the turn totals 3.1m which has been included in the total length of the turn. The sea tank is 1.5m wide, 15m long, with a working water depth of 1.5m and having a total volume of 34 m^3. Two side walls of the tunnel and all risers are constructed with Perspex allowing visual observation of flow patterns in the system. A bidirectional electromagnetic flowmeter is mounted on every riser to continually monitor flow rate and direction in each riser.

Riser Number	$\frac{\Delta\rho}{\rho_o}$	$Q_{P,E}$ (L/s)	$Q_{P,C}$ (L/s)	$\frac{Q_{P,E}}{dt}$ (L/s^2)	$\frac{Q_{P,C}}{dt}$ (L/s^2)
2	0.0083	0.6*	0.67	QS	0.0005
	0.0187	1.0*	0.96	QS	0.001
3	0.0201	2.0*	1.97	QS	Q_t
	0.0165	1.8*	1.84	QS	Q_t
	0.0120	1.5*	1.35	QS	Q_t
	0.0297	2.6*	2.36	QS	Q_t
	0.0176	1.7*	1.67	QS	Q_t
4	0.0204	3.2*	3.02	QS	Q_t
	0.0138	2.6*	2.49	QS	Q_t
	0.0185	2.9*	2.85	QS	Q_t
	0.0104	2.3*	2.27	QS	Q_t
6	0.0176	4.4	4.68	QS	Q_t
8	0.0204	7.2*	6.65	QS	Q_t
	0.0205	7.0	6.66	QS	Q_t
	0.0179	5.78	6.27	QS	Q_t
	0.0210	7.08	6.75	QS	Q_t
	0.0183	6.75	6.32	QS	Q_t
	0.0187	6.75	6.41	QS	Q_t
	0.0184	6.85	6.60	0.0040	0.0040
	0.0188	7.15	6.71	0.0109	0.0109

Note: (1) * – There is precirculation ;
(2) QS – Quasi-steady ;
(3) Q_t = 0.0015

Table 1: Comparison of experimental and calculated purging discharge

Under quasi-steady conditions, seawater purging process in the invert-connected outfall is quite different from that in the soffit connected outfall. For the diffuser with a upward slope, at the first period of purging, effluent will proceed through top of the tunnel and straight to the most seaward end, and a stratification is then formed. Flow in all risers is upward in a much longer time than it dose in a soffit-connected outfall during the first stage. Then the most seaward riser, particularly, if it is a soffit-connected one, is fed with more and more effluent and velocity of upflow in it becomes larger and larger. This process is followed by the second most seaward riser and then the next. Consequently, density balance between seaward risers and landward risers fails and landward risers become intruded. The tendency of purging from seaward risers to landward risers in the invert-connected diffuser with a upward slope can be strengthened by cross section of the tunnel tapering seaward. In the case of purging sequence from seaward to landward, saline wedge at the bottom of the tunnel moves in the same direction of effluent flow. In this situation k=0 is set in the numerical model.

However, if the diffuser tunnel of an invert-connected outfall is basically horizontal and cross section of it dose not significantly taper, purging sequence may be from landward to seaward, then saline wedge at the bottom of the tunnel will move in the opposite direction of effluent flow. Also for steady purging, sequence of purging is usually from landward to seaward. One more example is that there is precirculation before purging process starts. If the seaward risers are in intrusion during precirculation, in the cases that the pre-intrusion are strong the mode will remain after purging process has started. In the cases discussed above, saline wedge at the bottom of the tunnel will move in the opposite direction of effluent flow, then k≠0. In these cases, a constant value of, again, k=0.9 is used in the numerical model for invert-connected outfalls.

Precirculation is an important phenomenon for invert-connected outfalls. When effluent discharge becomes

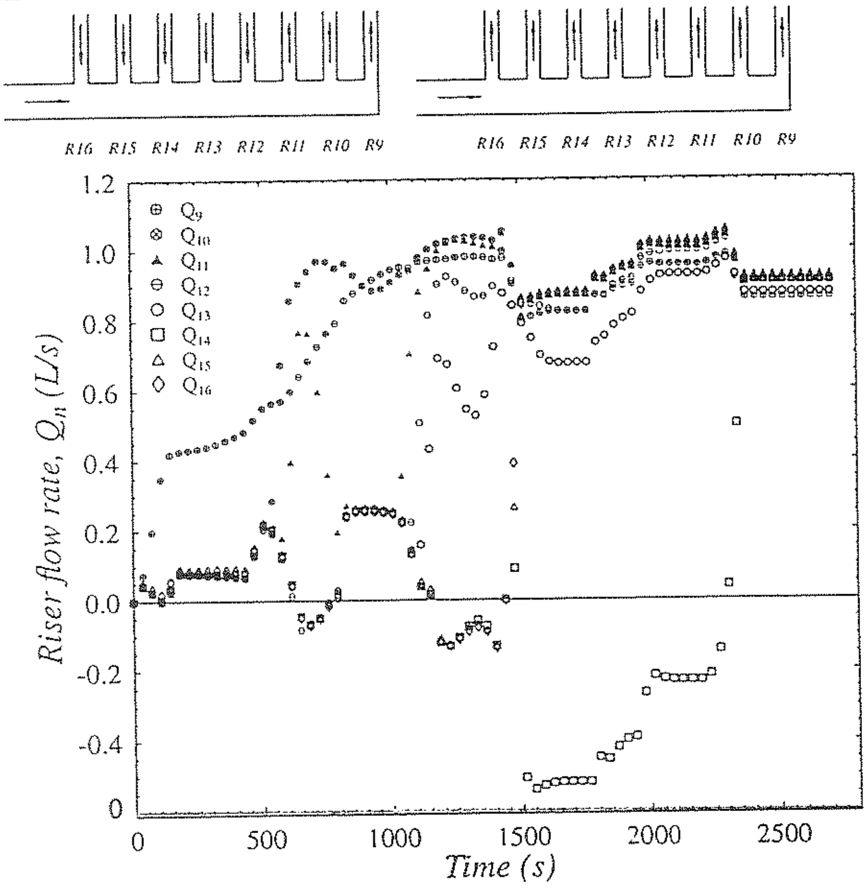

Figure2 : Calculated purging process (Effluent layer considered)

zero, seawater will soon intrude into the outfall tunnel and occupy the bottom part of the tunnel. If all risers are invert-connected, a quasi-stable stratification will form. Replacement of the effluent of less density in the top layer by seawater through circulation takes a very long time. Taking the Hong Kong model outfall as an example, though the most seaward riser is soffit-connected, in most experiments, only 8 or less risers are used, i.e., all risers are invert-connected in the experimental cases. Consequently, circulation dose not calm even 20 hours after effluent pump has been shut down and a thin layer of effluent can be seen at the top of the tunnel. Effluent remaining in the tunnel may make purging easier, on the other hand, however, precirculation may retard purging due to inertial effect. Experiments and calculation were all conducted and compared to study the effect of precirculation as shown in Table 1, where $Q_{P,E}$ and $Q_{P,C}$=experimental and calculated purging discharge rate, respectively. It is seen that purging discharge rate essentially increases with increase of riser number and density difference while precirculation has no significant effect on the purging discharge rate.

However, existence of the effluent layer at the top of the tunnel has significant effect on purging process. In numerical modelling, when the effluent layer is taken into account, the calculated purging process is very similar to the experimental one. Fig. 2 is an example of calculated purging process that is reasonably consistent with the measured process. Arrows in the figure indicate flow directions in the system at first and final period of purging. While if the effluent layer is not taken into account, the purging process is significant different. In that case, purging takes much longer time since density in the most seaward riser decreases very slowly though the purging discharge rate is the same. Usually, an invert-connected outfall has a soffit-connected riser most seaward. That will help removal of gas in the tunnel and also help quick completion of circulation in the system during the period when pump stops.

There is a essential difference between soffit- and invert-connected outfalls. In the situation of soffit connection, effluent wedge in the top layer firstly flows into the risers, while in the case of invert connection, saline wedge in the bottom layer firstly flows into the risers. When the thickness of the saline wedge reaches a critical value, effluent in the top layer will be drawn into flow in the riser. In this case, sometimes, sinks at junctions can be seen on the interface of stratification as shown in Fig. 3 (calculated result). Following studies conducted by Sharp et al (Sharp et al, 1991), the critical thickness h_c is defined as

$$h_c = d\left[1 + C_1 V_r \left(\frac{\Delta\varrho}{\varrho_o} g d\right)^{-0.5} + C_2 V_t \left(\frac{\Delta\varrho}{\varrho_o} g D_t\right)^{-0.5}\right]$$

where $C_1=0.3$ and $C_2=0.2$; V_r and V_t are velocities in the riser and in the tunnel, respectively; d is diameter of the riser, D_t is diameter of the tunnel and, $\Delta\rho=\rho_s-\rho_o$. Now (control volumes in Fig. 1 are refereed)

$$\varrho_2 = \varrho_s - \alpha(\varrho_s - \varrho) \qquad (10)$$

and

$$\alpha = 1 - \frac{h}{h_c} \qquad (11)$$

where the thickness of saline wedge, h, is defined in equation (9). If $h > h_c$, then $\alpha=0$. The constraint of mass conservation now gives

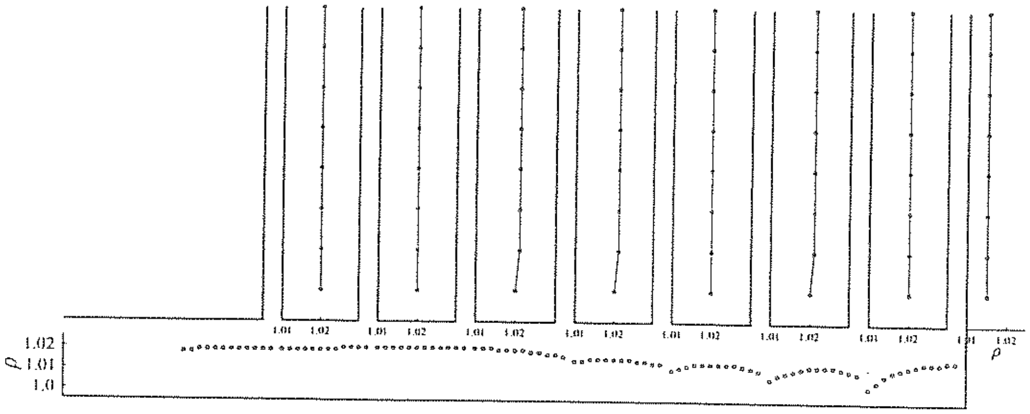

Figure 3: Density profile inside outfall tunnel ($\frac{\Delta\rho}{\rho_o}$ = 0.0205, t = 504s) — Interface with sinks at junctions

$$\varrho_3=\varrho-(1-\alpha)(\varrho_s-\varrho)\frac{A_2V_2}{A_3V_3} \qquad (12)$$

Although stratification is also significant in the invert-connected outfall, it is far not as clear as it is in the soffit-connected outfall. That, on the other hand, means that mixing in the invert-connected outfall is much stronger than in the soffit-connected outfall. Therefore a larger dispersion coefficient is applicable. In this study, m=6.5 is adopted in equation (7). This is equivalent to a=18.38.

CONCLUSION AND REMARKS

The numerical model developed by Guo and Sharp (1996) is extended to be applicable to invert-connected sea outfalls in this paper and is applied to Hong Kong model outfall. By comparing with experiment observations, it is shown that the innovated model can not only give general results, such as purging discharge, consistent with measured results, but also predict every details that are observed in the experiments, though for a lager scale model as Hong Kong model outfall is the case, there are inevitably some random factors interfering experiment and sometimes cause uncertainty of measurement results.

Experiment observation and numerical calculation demonstrate that purging process and mechanism of invert-connected outfalls are very different from that of soffit-connected outfalls. These differences can not be taken into account by use of Munro head method. Firstly, in invert-connected situation sea water at the bottom of the tunnel is purged at the first period of purging, while in soffit-connected situation effluent at the top of the tunnel flows into the riser first. Secondly, mixing between effluent and seawater in invert-connected situation is much stronger than that in soffit-connected situation. Thirdly, purging sequence in invert-connected situation is usually from seaward end to landward end for unsteady and quasi-steady purging though it is also, like in soffit-connected situation, from landward end to seaward end for steady purging. Finally, if there exists effluent layer at the top of the tunnel, it will maintain a circulation very long time and affect purging sequence.

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