Numerical and experimental study of unsteady salt water purging in Hong Kong sea outfall model

Etude numérique et expérimentale de la vidange instationnaire d'eau salée dans l'émissaire en mer de Hong Kong

JOSEPH H. W. LEE, *Professor, Department of Civil Engineering, The University of Hong Kong, Hong Kong, China*
ZHEN-REN GUO, *Professor, Deputy Director, South China Institute of Environmental Sciences, Guangzhou, China*
TONY W. C. YAU, *Research Assistant, Department of Civil Engineering, The University of Hong Kong, Hong Kong, China*

ABSTRACT
Based on experiments on the 1:20 Hong Kong model diffuser, a numerical model for simulating seawater intrusion and purging process in an invert-connected outfall is developed. An extension of the theory of Guo and Sharp (1996), this is essentially a one dimensional unsteady flow model with locally 2D techniques to account for stratification and density changes at riser-tunnel junctions. Numerical predictions of purging flow and times are in good agreement with measurements; key features of the purging sequence are also well-supported by the synoptic observed riser flows.
Both experiments and calculations demonstrate that, unlike a soffit-connected outfall, the seawater at the bottom of the tunnel is initially purged, and the mixing between effluent and seawater is much stronger. The purging sequence in invert-connected situation is usually from seaward end to landward end for unsteady and quasi-steady purging; however for steady purging the sequence is from landward end to seaward end as in soffit-connected outfalls. The presence of an effluent layer at the top of the tunnel (due to e.g. pump shutdown) results in a persistent circulation in the system. The numerical model also shows that shortening the outfall tunnel length by an artificial bend has an effect on the purging sequence and time, but not the purging flow. Two-layer purging occurs in steady purging process and can help reduce purging discharge rate, especially with a large number of risers. Salt-assisted purging is effective only if the duration of the process is sufficiently long; however, the effluent volume required can be larger than that in the pure effluent purging process.

RÉSUMÉ
Sur la base d'expériences menées dans le diffuseur 1:20 de Hong Kong, un modèle numérique a été développé pour simuler l'intrusion des eaux salines et les opérations de purge dans un canal exutoire . En extension de la théorie de Guo et Sharp (1996), c'est essentiellement un model 1D instationnaire, localement bidimensionnel pour prendre en compte la stratification et les changements de densité aux jonctions riser-galerie d'amenée. Les prédictions numériques des écoulements de purge et des temps associés montrent une bonne concordance avec les mesures; les particularités des séquences de purge sont également bien représentées par la synoptique des écoulements observés dans le riser.
A la fois les expériences et les calculs montrent que, malgré un exutoire noyé (avec une partie en contrepente), l'eau de mer au fond du canal est d'abord purgée, et que le mélange entre effluent et eau saline est alors le plus fort. La séquence de purge dans un emissaire se fait habituellement du large vers la terre dans le cas de purges instationnaires ou quasi-stationaires; Cependant pour un nettoyage permanent l'opération se fait de la terre vers le large, comme dans un exutoire noyé (in soffit-connected outfalls).
La présence d'une couche d'effluent au sommet du tunnel (due à un arrêt du pompage) persiste dans le système. Le modèle numérique montre aussi que le raccourcissement du canal exutoire (en simulant cette réduction de longueur) a un effet sur les séquences et leur durée, mais pas sur les écoulements. Deux couches apparaissent dans le processus stationnaire et peuvent aider à reduire les débits de purge, spécialement lorsqu'il y a un grand nombre de riser. La purge en sel est effective seulement si la durée du process est assez longue, et le volume d'effluent requis peut être plus important que dans le cas d'une purge de l'effluent seul.

Introduction

As part of the Strategic Sewage Disposal Scheme (SSDS), a large deep tunnelled sea outfall has been designed to dispose treated sewage from a population of 3.5 million in Hong Kong into the sea. The outfall diffuser belongs to the invert-connected type according to the preliminary design. A scale model of the outfall diffuser, probably the largest of its kind, has been designed and constructed to study the seawater purging process (Charlton 1991; De Jong and Delvigne, 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 solve this problem (e.g. Charlton, 1982, 1985; Brooks, 1988; Wilkinson, 1984, 1988; Burrows et al, 1991). Many small outfalls and some old, longer outfalls are soffit-connected with riser offtakes perpendicular to the soffit of the outfall tunnel. Many previous studies have focused on this type of outfalls (Wilkinson, 1984, 1985; Guo and Sharp, 1996; Burrows et al, 1996). On the other hand, most modern large deep tunnelled sea outfalls are constructed with riser offtakes flush with the invert of the outfall tunnel. Differences in purging behaviour between soffit- and invert-connected outfalls have been pointed out by some investigators (Charlton, 1985); seawater purging experiments with scale models of invert-connected outfall have also been reported (Adams et al, 1994; De Jong and Delvigne, 1994).

It is usually believed that the invert connection can help reduce the purging discharge required to remove any intruded seawater from the outfall. However, this conclusion cannot be reached on the basis of the Munro head that cannot discern any structural difference between soffit- and invert-connected outfalls; a meaningful analysis of the problem would have to resort to a numerical model. Nevertheless, previously developed numerical models mainly focused on soffit-connected outfalls (Larson et al, 1989, 1992; Guo and Sharp, 1996); numerical simulation of the unsteady purging in an invert-connected outfall has hitherto not been reported.

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This paper reports a numerical and experimental study of seawater intrusion and purging in the Hong Kong outfall model. First, a general numerical model for simulating the unsteady purging in an invert-connected outfall is described. This model is an extension of the model of Guo and Sharp (1996) previously developed for soffit-connected outfalls. For brevity, only the model formulation and essential model details pertaining to invert-connected risers are included. Second, the key experimental observations on the Hong Kong model, which have aided the numerical formulation and provided data for model calibration, are described. In particular, the numerical model is used to interpret the sometimes perplexing purging sequences observed. Predicted purging flow rates and sequences are compared with experimental data and discussed. Finally, the numerical model is used to investigate a) the effect of shortening the outfall diffuser length in a scale model by a 180 degree bend; and b) the effectiveness of two-layer and salt-assisted purging.

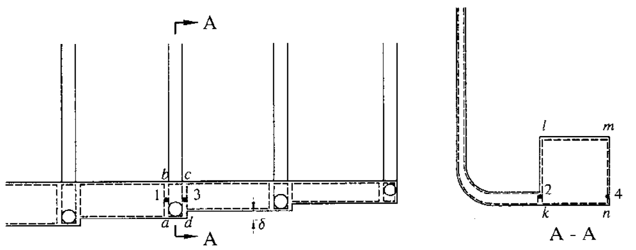

Fig.1a. Outline of grid for flow calculation.

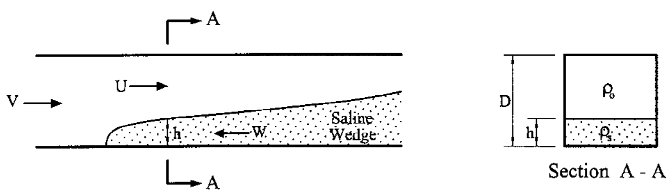

Fig.1b. Definition of Variables in Stratified Tunnel.

Numerical Model

The numerical model basically follows the same approach as detailed in Guo and Sharp (1996). It is essentially a one-dimensional model for describing the transient flow and density distribution along the tunnel and riser sections, with some locally two-dimensional techniques to account for stratification effects and density changes across the riser-tunnel junction. Fig. 1a) shows the grid system employed for the flow calculation. For tunnel segments and risers with uniform cross sections, the following momentum equation for unsteady flow is adopted:

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

where ρ, V are respectively the average fluid density and velocity in the cross section; P=pressure at centre of cross-section; λ=friction factor; ψ= hydraulic radius (=D/4 for a round pipe of diameter D or for a square conduit of side length D), g=gravitational acceleration; x=distance along flow direction; t=time, and θ=vertical angle of flow direction with horizontal plane. Using such grid system, sudden changes in tunnel cross section as in the Hong Kong outfall model can be readily handled.

At a Tee junction (Fig. 1a), the momentum principle can be applied to the control volume *a-b-c-d* for the axial direction of the tunnel and the control volume *k-l-m-n* for axial direction of the riser offtake. In this way, it can be shown that

$$P_1 + P_3 = \left(\frac{A_3}{A_1}\right)\rho_3|V_3|V_3 - \rho_1|V_1|V_1 + \frac{\delta}{2}\rho_3 g \qquad (2)$$

and

$$P_1 - P_3 - 2P_2 = 2\rho_2|V_2|V_2 - \left(2z + \frac{\delta}{2}\right)\rho_3 g \qquad (3)$$

where A=cross-section area, and subscripts indicate locations of the respective cross sections; z=vertical distance between the centre of cross section of the tunnel and that of the riser offtake; δ=height of the step in the tunnel. In the above deduction, it has been assumed that

$$P_4 = \frac{1}{2}\left(P_1 + P_3 + \frac{\delta}{2}\rho_3 g\right) \qquad (4)$$

By accounting for head losses at the riser heads, the energy equation can be used to relate riser velocities and pressures and water depth outside. Flow continuity at each junction gives

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

where Q=discharge. To account for effects of stratification, the salinity distribution is computed by a modified transport-dispersion equation:

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

where as shown in Fig.1b) W is the velocity of saline wedge, in opposite direction to V; this counterflow effect on the salt transport is considered with a modification coefficient k<1. The dispersion coefficient, E, is related to the velocity and geometric dimension as:

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

where the friction velocity $u^*=(\lambda/8)^{0.5}V$, and $m=a/8^{0.5}$. The value of m is obtained from experiments as discussed later.

The motion of a saline wedge in the tunnel (Fig.1b) is analysed by drawing an analogy to the motion of a saline wedge in an open channel. The relative velocity of the saline wedge, U+W, is assumed to depend on the relative density, layer thickness and bottom slope in the same way as a classical wedge, with the overall constraint of salt mass conservation in the tunnel. Considering the relative motion between the top effluent layer and bottom saline wedge (Fig.1b), and invoking fluid and salt mass continuity as before (Guo and Sharp, 1996), it can be shown that for a square cross section we have:

$$h = \frac{D(\rho - \rho_o)}{\rho_s - \rho_o} \tag{8}$$

and

$$U = \frac{\rho_s - \rho_o}{\rho_s - \rho} V + \frac{\rho - \rho_o}{\rho_s - \rho} W \tag{9}$$

where h=thickness of saline wedge in the tunnel; ρ_o and ρ_s are effluent and sea water densities respectively. Since the relative velocity $U+W= \sqrt{(1+\sin\theta)2\frac{\Delta\rho_o}{\rho_o}gh}$,

where θ = local slope of the invert, it can be shown that

$$W = \frac{D-h}{D}\left[(1-\sin\theta)2gh\frac{\rho_s - \rho_0}{\rho_o}\right]^{0.5} - V \tag{10}$$

With an additional relation between the fluid density of the mixed flow into the riser and the average fluid density in the junction (see next section), the governing equations are complete. Given the initial conditions, Eq. 1, 5 and 6 can be solved using a finite volume-based numerical solution algorithm; details can be found in Guo and Sharp (1996).

Intrusion and purging in the invert-connected outfall

The development of the numerical model is much aided by observations on the Hong Kong model outfall. Comparisons are made between calculated and observed results to calibrate the numerical model. The numerical model is also used to interpret the observed characteristics of intrusion and purging in the invert-connected outfall.

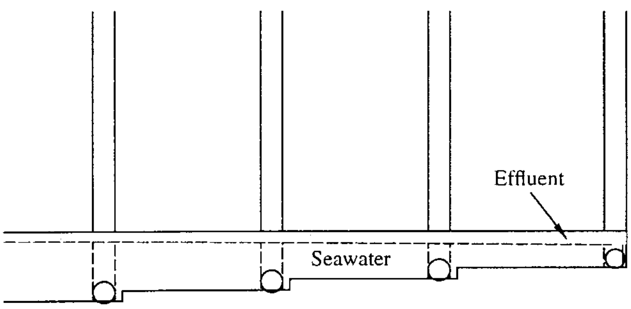

Fig. 2. Observed stratification at first period of purging.

The model outfall is a 1:20 densimetric Froude scale model originally designed for short term use by Delft Hydraulic Laboratory (Charlton 1991; De Jong and Delvigne, 1994); it was subsequently refurbished into a research facility (Lee and Yau 1996; Yau 1997). The model basically consists of a diffuser tunnel section, a sea tank, and a fresh water supply system. The diffuser tunnel of the model is 33.2m long, with a variable square cross-section initially 248mm high and then tapering seawards; the tunnel soffit is horizontal while the invert slopes upwards at approximately 1:500. Sixteen vertical risers (each 8.75 m high with internal diameter 44 mm) are connected from an upper sea tank to the invert of the tunnel (except the most seaward one) and spaced at 1875mm apart. For practical reasons, the length of the diffuser is shortened by half via a 180 degree bend at mid-length; there are eight risers before the bend and another eight after the bend. 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. The side walls of the tunnel and all risers are constructed with Perspex allowing visual observation of flow patterns in the system. A bi-directional electromagnetic flowmeter is mounted on every riser to continually monitor flow rate and direction in each riser. Pressure measurements can be made at various points in the tunnel and riser, enabling head loss characteristics to be independently measured. Sea water and effluent densities are obtained from temperature and conductivity measurements. Further, a freshwater inflow hydrograph can be generated by an electric valve actuator controlled by a step motor and signal generator. Additional details on the experimental set up can be found in Yau (1997). To complement the numerical model, a series of specially-designed experiments on unsteady purging has been conducted with different number of risers (2 to 8), density differences, and mode of purging; a summary of experimental parameters is given in Table 1. For these experiments, the landward 8-riser section of the model diffuser is blocked off. In each experiment, the freshwater effluent flow is progressively increased either in a quasi-steady manner or according to a prescribed rate of increase, and the time variation of riser flows recorded. Flow visualisation experiments with the aid of dye injection were also performed.

Under quasi-steady conditions (effluent flow rate increases in a stepped manner), in the invert-connected diffuser with an upward slope, it is observed that the effluent proceeds through top of the tunnel and straight to the most seaward end in the initial stage of purging; a stratification as shown in Fig. 2 is formed. The flow in all risers is upwards for a much longer time than previous observations for soffit-connected outfalls. Then the most seaward riser (especially if it is a soffit-connected one) is fed with more and more effluent with corresponding increase of upflow velocity. This process is followed in the second most seaward riser, and then the next. Consequently, through the discharge of freshwater from more seaward risers, there is less internal pressure in the tunnel to push the heavier seawater out of the landward risers which then become intruded. This observed purging process is predicted in the numerical calculations which also reveal that the tendency of purging from seaward to landward risers can be strengthened by the seaward tapering cross section of the tunnel. For the seaward to land

Table 1. Comparison of experimental and calculated purching discharge.

Riser Number	$\frac{\Delta\rho}{\rho_o}$	Q_{PE} (L/s)	Q_{PC} (L/s)	$\frac{Q_{PE}}{dt}$ (L/s^2)	$\frac{Q_{PC}}{dt}$ (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 L/s^2

ward purging sequence, the saline wedge at the bottom of the tunnel moves in the same direction of effluent flow (i.e., $W<0$). In this situation $k=0$ is set in the numerical model.

There are some cases in which $W>0$. Numerical experiments show that if the diffuser tunnel of an invert-connected outfall is basically horizontal and the cross-section does not significantly taper off, a landward to seaward purging sequence can result, in which case the bottom saline wedge moves in the opposite direction to the effluent flow ($W>0$). Both experiments and model calculations show that this situation occurs for steady purging (constant effluent flow rate), and when there is a pre-circulation in the diffuser before purging process starts. If the seaward risers are being intruded in pre-circulation and the pre-intrusion is strong, the mode can remain after purging process has started. For all these cases with a stratified counterflow, a constant value of $k=0.9$, the same value as that used for soffit-connected outfalls, is adopted.

Pre-circulation, resulting from pump shutdown or a previous different operation, is an important phenomenon in invert-connected outfalls. It is observed that when the pump is shut down

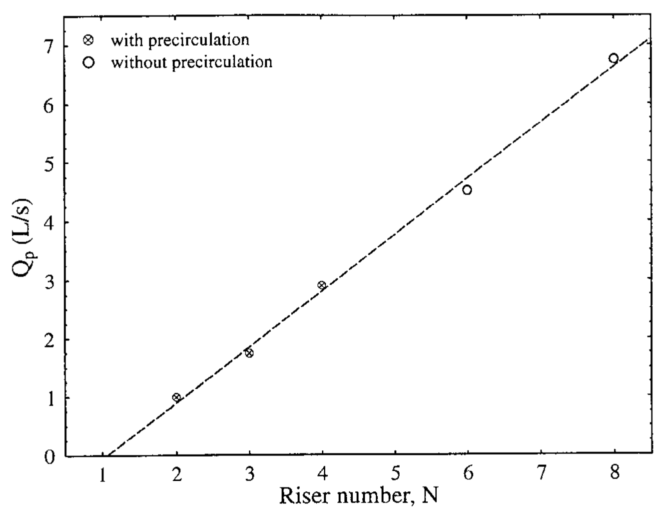

Fig. 3. Experimental purging discharge as function of riser number $\left(\frac{\Delta\rho}{\rho_o} = 0.0185\right)$

and effluent discharge becomes zero, seawater soon intrudes into the outfall tunnel and occupies the bottom part of the tunnel. If all risers are invert-connected, a quasi-stable stratification similar to that shown in Fig. 2 results. Replacement of the less dense effluent in the top layer by seawater through circulation takes a very long time. In our experiments, all the risers are invert-connected as only the 8 most landward risers (R9 to R16 in Fig.4-7) were used. Consequently, the circulation did not dissipate even 20 hours after the effluent pump has been shut down, and a thin layer of effluent can still be seen at the top of the tunnel. The effluent remaining in the tunnel may make purging easier; on the other hand, the pre-circulation may retard purging due to inertial action. Fig. 3 shows measured purging discharge rates with pronounced and negligible pre-circulation at $\Delta\rho/\rho_o=0.0185$. It can be seen that purging discharge increases linearly with increase of only riser number and pre-circulation has no significant effect on purging discharge rates. The insensitivity of the required purging flow to any pre-existing circulation has previously been noted (Wilkinson 1985; Lee and Yau 1996), and can also be seen from the comparison between experimental and computed results over a broader range of experimental parameters in Table 1. However, the existence of the effluent layer at the top of the tunnel has a significant effect on purging process. When the effluent layer is taken into account (by setting initial condition of density of water in the tunnel), the calculated purging process (Fig. 4) is very similar to that measured (Fig. 5). Ignoring the effluent layer in the model results in a significantly different purging process (Fig. 6). In the latter case, purging takes a much longer time since the density in the most seaward riser decreases very slowly - although the purging discharge rate is the same. The significant intrusion into some risers, e.g. R14, also cannot be simulated. In Fig. 4-6, the purging sequence is indicated by the measured time variation of riser flows; the arrows in the top of the figures indicate flow directions in the system at first and final stage of purging.

Invert-connected outfalls usually have a soffit-connection for the most seaward riser; this will facilitate removal of gas in the tunnel and quick completion of circulation in the system during shutdown of the pump.

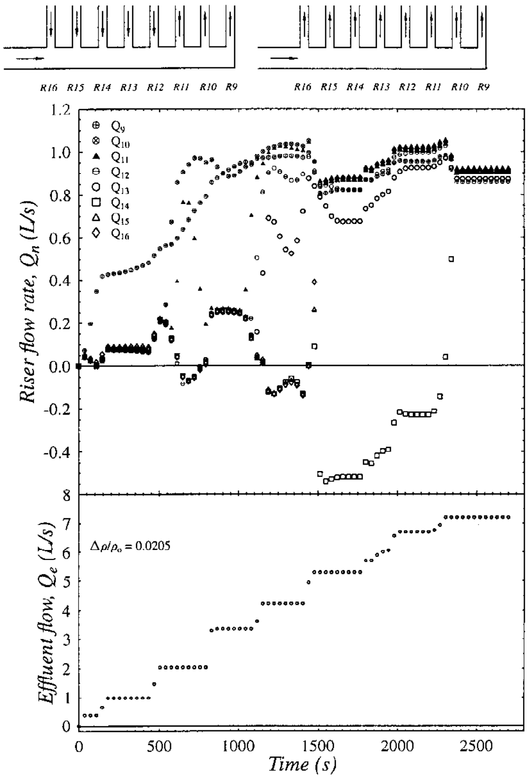

Fig. 4. Calculated purging process (Effluent layer concidered).

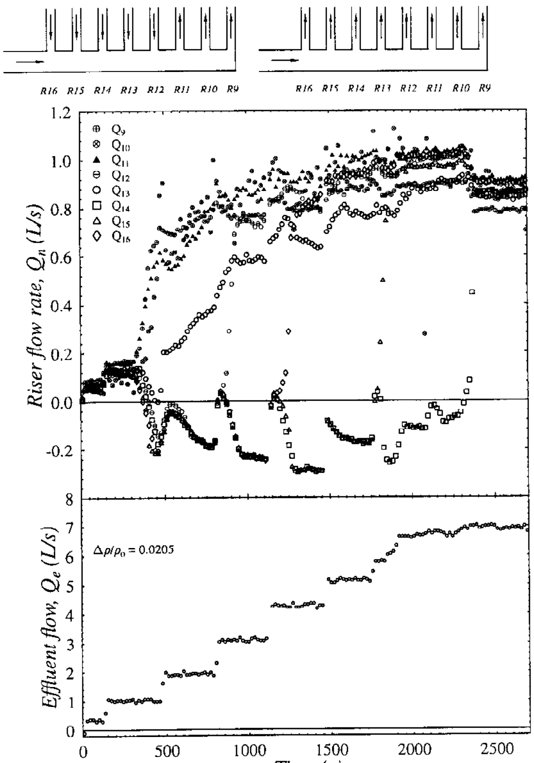

Fig. 5. Measured purging process (Effluent layer exists).

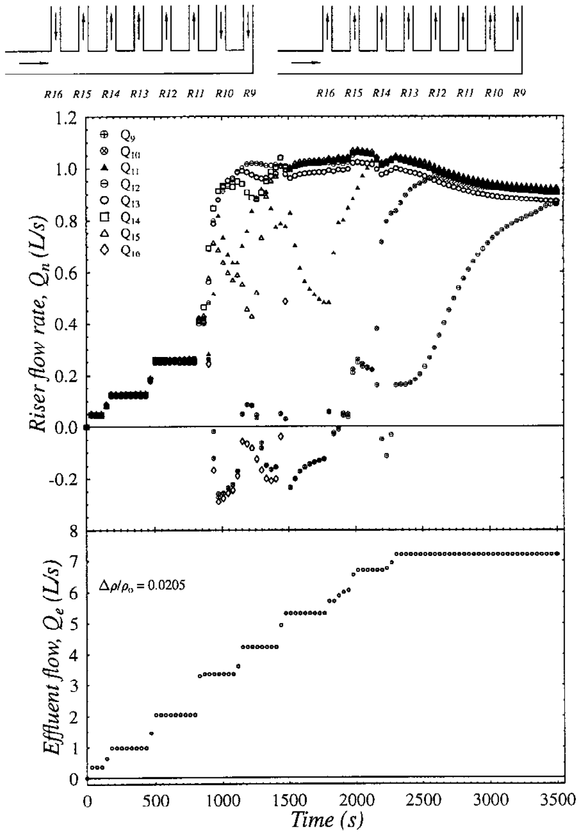

Fig. 6. Calculated purging process (Effluent layer not considered).

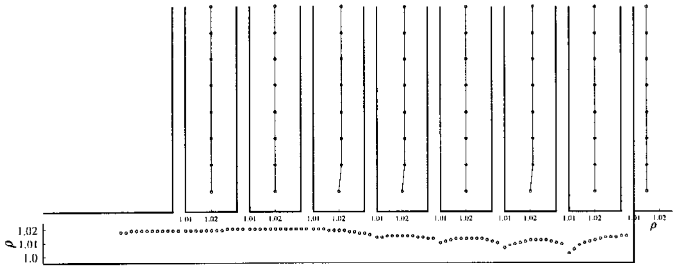

Fig. 7. Computed density profile inside outfall tunnel corresponding to observed interface with sinks at junctions

$$\left(\frac{\Delta\rho}{\rho_o} = 0.0205,\ t = 504\mathrm{s}\right)$$

There is an essential difference between seawater purging of soffit- and invert-connected outfalls. In the former case, the effluent in the top layer firstly flows into the risers, while for the latter case, the saline wedge in the bottom layer firstly flows into the risers. For invert-connected outfalls, when the thickness of the saline wedge drops to a critical value, the 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, and accompanied by significant density drops around junctions, as shown in Fig. 7. Following studies conducted by Sharp et al (Sharp et al, 1991; Sharp et al, 1996) on the selective withdrawal threshold, the critical thickness h_c is defined as

$$h_c = d\left[1 + C_1 V_t\left(\frac{\Delta\rho}{\rho_o}gd\right)^{-0.5} + C_2 V_1\left(\frac{\Delta\rho}{\rho_o}gD_t\right)^{-0.5}\right]$$

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, $\Delta\rho=\rho_s-\rho_o$. Referring to the control volumes in Fig.1, and applying a salt balance, the density of the fluid flowing into the riser, ρ_2, can be related to the average density of water in the junction, ρ , as follows:

$$\rho_2 = \rho_s - \alpha(\rho_s - \rho) \tag{11}$$

and

$$\alpha = 1 - \frac{h}{h_c} \tag{12}$$

where the thickness of saline wedge, h, is defined in equation (8). If $h>h_c$, then α=0. The constraint of mass conservation now gives the density change across the junction in the tunnel:

$$\rho_3 = \rho - (1-\alpha)(\rho_s - \rho)\frac{A_2V_2}{A_3V_3} \tag{13}$$

The experimental observations show that although the stratification is significant in the invert-connected outfall, it is not as distinct as for the soffit-connected outfall, suggesting much stronger mixing in the invert-connected outfall. Based on the experiments, a larger dispersion coefficient with m=6.5 (i.e. a=18.38) is hence adopted in equation (7).

Table 2. Calculated Purching Discharges with and without Consideration of Bend.

ρ_s	1.01	1.015	1.02	1.025	1.03
Q_p without bend	10.88	13.35	15.38	17.18	18.80
Q_p with bend	10.91	13.35	15.43	17.22	18.86

Effect of a bend on purging in a model outfall

As previously described, for practical reasons it is often necessary to reduce the length of a scale model via a bend; in particular the diffuser tunnel of Hong Kong model outfall is turned through 180° at mid-length. For similar reasons, such arrangements may be made with any other model outfall. For instance, a distorted model is used for the Boston outfall study (Adams et al, 1994), and only two risers are included in a model of the Sydney outfall (Wilkinson, 1992). It is desirable to study numerically the effect of such changes in geometry on intrusion and purging in a scale model. The tunnel bend effect in the Hong Kong model outfall is simulated by including both the length of the bend (=3.1m including transitions) and a local head loss in the numerical model. Table 2 shows the calculated purging discharges of Hong Kong model outfall with and without consideration of the bend. It is seen that in the case of unsteady purging in which effluent flow rate increases linearly (increase rate dQ/dt=0.003 L/s^2), the bend results only in a negligible change of computed purging flows. However, as seen in Figure 8 and 9, the purging sequence is very different in the two cases since the bend changes pressure distribution in the system. In the figures, the arrows indicate the flow directions in the system in the first stage of purging. The calculations also show that in the case of steady purging (again $\Delta\rho/\rho_o$=0.02), Q_p=11.8 L/s when bend is considered and Q_p=11.5 L/s when no bend is considered - again a very small difference. The purging times can however be quite different. Figure 10 and 11 show that in the case where no bend is considered, seawater is nearly purged at t=216s after purging has started; purging is complete at T_p=330s. In the presence of a bend, a large amount of seawater still remains in the tunnel behind the bend at t=216s because of the resistance at the bend; consequently the system does not purge until T_p=420s. As previously noted (Adams et al, 1994), the purging time is related to the volume of freshwater needed to purge the outfall.

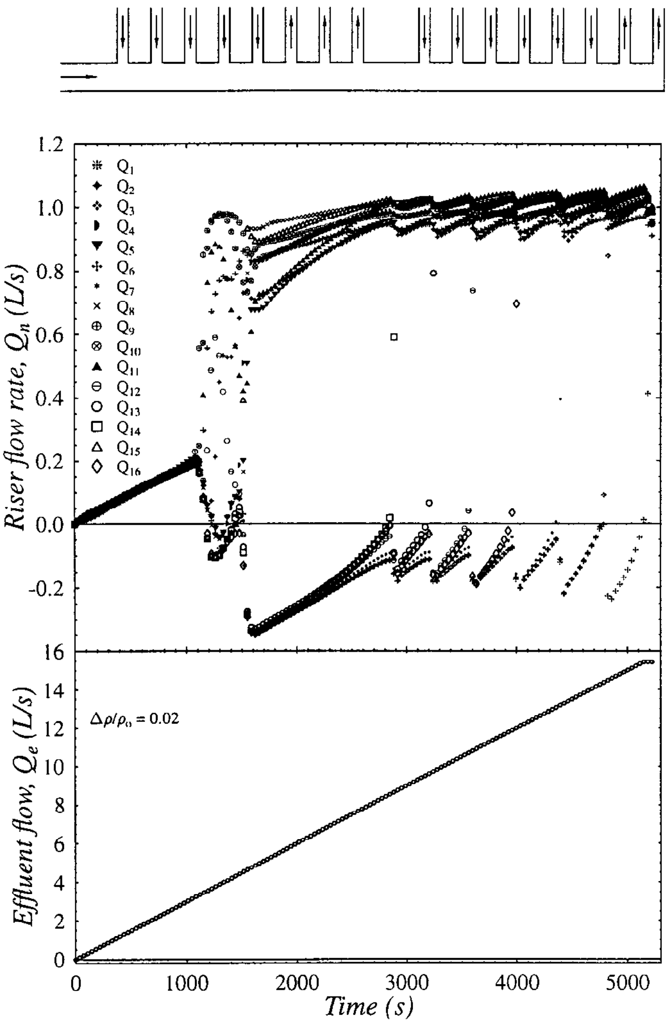

Fig. 8. Calculated purging process (Bend considered).

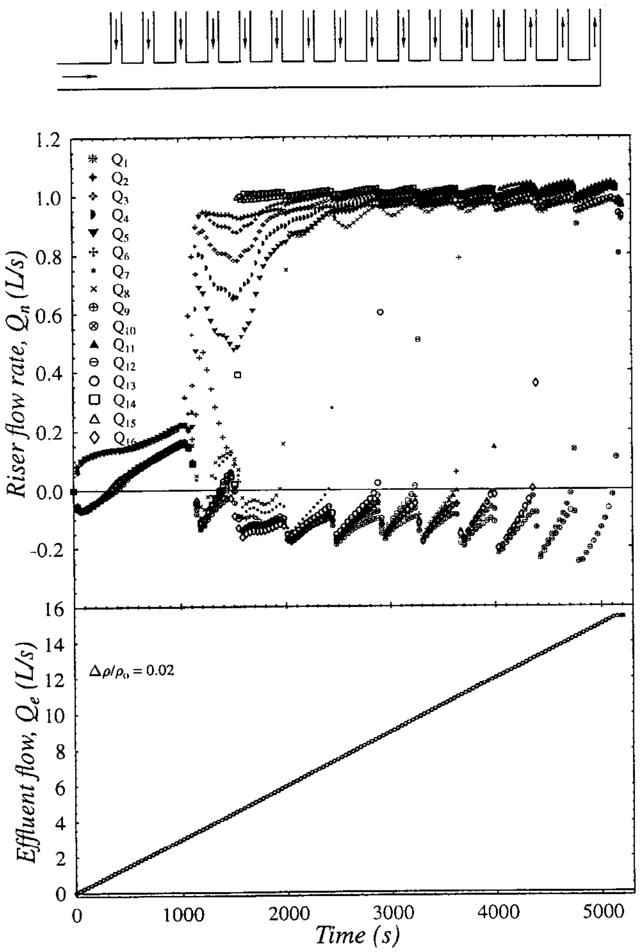

Fig. 9. Calculated purging process (Bend not considered).

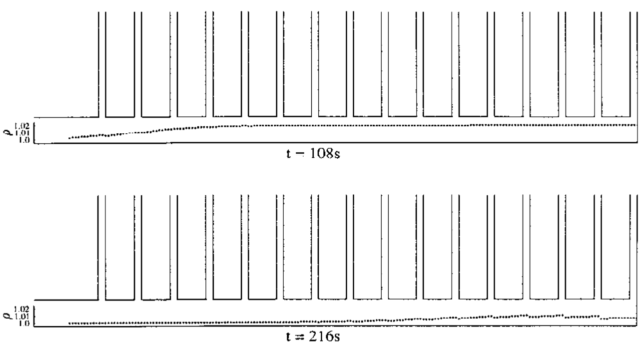

Fig. 10. Computed density profile inside outfall tunnel (without bend consideration).

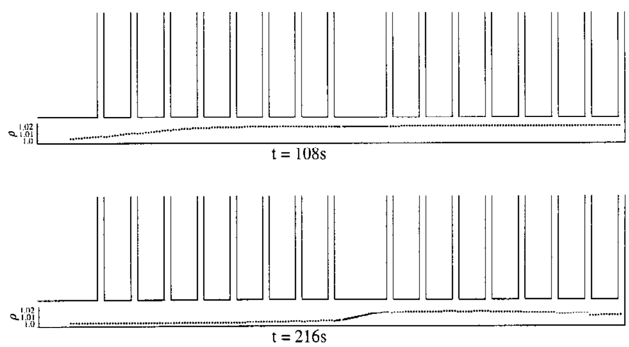

Fig. 11. Computed density profile inside outfall tunnel for steady purging (with bend consideration).

Two-layer purging and salt- assisted purging

The so-called two-layer purging occurs under the situation of steady purging. According to De Jong et al (1994), in the case of two-layer purging, the density in the outfall tunnel should increase seawards as seen in Figure 10 and 11, different from that shown in Figure 7. For two-layer purging, purging discharges are usually smaller than that in unsteady purging and quasi-steady purging. It is noticed from the numerical calculation that the difference between purging discharge rate of unsteady and steady purging increases with the number of risers. For instance, in the case described in above section where 16 risers are involved, the difference is about 24%. When 8 or less risers is involved, the difference is usually less than 6%. Purging discharges of quasi-steady purging fall between those of steady and unsteady purging when other conditions are the same.

Salt-assisted purging can be a practical operation in which the effluent is mixed with a portion of seawater. The initial density of mixed effluent can be between the densities of seawater and pure effluent and then it decreases to the density of the pure effluent. Table 3 gives seven calculated examples of salt-assisted purging. A few points can be drawn from the calculated results. First, if the density of mixed effluent is constant and suddenly decreases to the density of pure effluent, the salt-assisted purging may not be able to reduce the purging discharge (Case 1, 2, and 3). Second, by decreasing the density of mixed effluent gradually to the density of pure effluent, it is possible to reduce the purging discharge. However, for the same effluent discharge, only if the salt-assisted process lasts long enough can the system be successfully purged; otherwise the system would remain intruded (Case 4 and 5). This principle has been revealed by De Jong et al (1994) through their experiments. Third, an increase in duration of salt-assisted process would reduce purging discharge. This can be seen by comparing Case 6 and 7 to Case 4 and 5 in Table 3.

Table 3. Calculated Results of Salt-assisted Purging.

Case	Q_e (L/s)	Purging Time	$\rho_{(t)}$
1	10.0	intruded	1.01 (t<300s); 1.0 (t≥300s)
2	10.0	intruded	1.005 (t<350s); 1.0 (t≥350s)
3	10.5	intruded	1.01 (t<350s); 1.0 (t≥350s)
4	10.0	intruded	1.02-0.0004t (t<500s); 1.0 (t≥500s)
5	10.0	1207.2s	1.02-0.0002t (t<1000s); 1.0 (t≥1000s)
6	8.0	intruded	1.02-0.0002t (t<1000s); 1.0 (t≥1000s)
7	8.0	2185.2s	1.02-0.0001t (t<2000s); 1.0 (t≥2000s)

The effect of a bend on the salt-assisted purging is considered. Calculation shows that for ρ_t=1.02-0.0002t (t<1000s), when no bend is taken into account, Q_p=8.9 L/s and T_p=1227.6s; with a bend Q_p=8.6 L/s and T_p=1248s. It is interesting to note that this is contrary to the case of pure effluent purging, where the bend usually results in a slightly larger purging flow. In salt-assisted purging, the resistance at the bend forces the mixed effluent to flow out of the system more evenly through the risers in front of and behind the bend, making the density distribution among the risers more balanced. This can be seen by comparing Figure 12 to Figure 13. In both cases Q_e=8.6 L/s and ρ_t=1.02-0.0002t (t<1000s). The system with the bend is finally purged, while the system without bend remains intruded after t=792s because densities in landward risers are significant larger than that in seaward risers. The interpretation of observations of purging sequences in a model diffuser must hence be treated with caution.

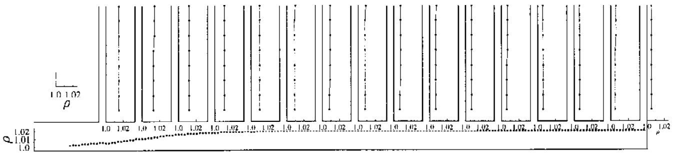

Fig. 12. Density profile inside outfall tunnel of salt assisted purging (*without* bend consideration) at t = 792s.

Concluding remarks

The numerical model of Guo and Sharp (1996) is extended to study unsteady seawater purging in invert-connected sea outfalls. The novel model formulation is based on a series of experiments performed in an 8-riser section of the diffuser model of the proposed Hong Kong outfall. The numerical model has proved most useful in the interpretation of the observed purging sequences in the large scale model. In general, the predicted purging sequences and many important flow characteristics are well supported by the observations. In particular, computed purging flows and times are in very good agreement with experiments. Differences in various details between computations and measurements (e.g. exact phasing of flow reversal) are inevitable due to various errors in the large scale model (e.g. unknown initial density distribution or riser flows), the inherent hydrostatic instability in the system, and in view of the relative simplicity of the model formulation. Since the calculations are done on a densimetric Froude scale model, the calculations on the model diffuser can be directly translated to the prototype.

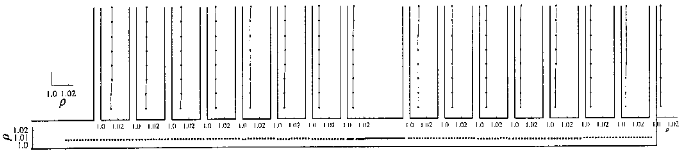

Fig. 13. Density profile inside outfall tunnel of salt assisted purging (*with* bend consideration) at t = 792s.

Both experiments and calculations demonstrate that the purging process in an invert-connected outfall is significantly different from that in a soffit-connected outfall. First, in invert-connected situation seawater at the bottom of the tunnel is initially purged, while in soffit-connected situation effluent at the top of the tunnel flows into the riser first. Second, the mixing between effluent and seawater is much stronger in the invert-connected outfall. Third, the purging sequence in invert-connected situation is usually from seaward end to landward end for unsteady and quasi-steady purging; however for steady purging the sequence is from landward end to seaward end as in soffit-connected outfalls. Finally, if there is an effluent layer at the top of the tunnel, it will maintain a circulation in the system very long time during the period of shutdown of the pump and may affect purging sequence in next operation. The numerical model has also been used to study the effect of shortening the outfall length by a bend, and other measures of assisting seawater purging. Important insights not obtainable with a physical model are gained. In particular, the addition of an artificial bend in the tunnel has an effect on the purging sequence and time, but not the purging flow. Two-layer purging happens in steady purging process and can help reduce purging discharge rate, especially with a large number of risers. Salt-assisted purging is effective only if the duration of the process is sufficiently long; however, the effluent volume required for purging can be larger than that in the pure effluent purging process.

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Notation

The following symbols are used in this paper:

A = cross-section area;
a = coefficient;
C = constant;
d = diameter of outfall riser;
D = diameter (general);
D_t = diameter of outfall tunnel;
E = dispersion coefficient;
g = gravitational acceleration;
h = thickness of saline wedge;
h_c = critical thickness of saline wedge;
k = coefficient;
m = coefficient;
P = pressure;
Q = discharge (general);
Q_e = discharge of effluent;
Q_n = discharge in outfall riser;
Q_p = purging discharge;
Q_{PC} = calculated purging discharge;
Q_{PE} = experimental purging discharge;
Q_t = increase rate of effluent discharge;
T_p = purging time;
t = time;
$u*$ = friction velocity;
V = average velocity (general);
V_r = velocity in outfall riser;
V_t = velocity in outfall tunnel;
W = velocity of saline wedge in outfall tunnel;
x = distance along flow direction;
z = vertical distance between centre of outfall tunnel and centre of riser offtake;
α = modification coefficient;
δ = height of step in outfall tunnel;
$\Delta\rho$ = ρ_s-ρ_o;
θ = angle of flow to horizontal plane;
λ = friction factor;
ρ = instantaneous density;
ρ_o, ρ_s = density of effluent and salt water;
ρ_t = density of mixed effluent; and
ψ = hydraulic radius.