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CIRCULATION BLOCKING OF TUNNELLED OCEAN OUTFALLS

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SUMMARY A new mechanism by which tunnelled outfalls can be rendered partially ineffective is described. The condition can develop when attempting to restart sewage flow following a shut down and is characterised by a blocking of sewage discharge from the nearshore risers. Means by which this condition may be rectified are discussed.

1 INTRODUCTION

In recent years, ocean disposal of sewage wastes has become an attractive option to public health authorities faced with ever increasing waste qualities and a reduction in suitable areas for land based sewage treatment. It is desirable that the ocean disposal sites be located away from areas frequented by the public, a criteria which to date has unfortunately not been adhered to in the Sydney region. In an effort to improve water quality along the Sydney beaches, it is proposed that sewage wastes be pumped offshore inside submarine tunnels and discharged into the ocean some kilometres off the coast. Water depths at the tunnel outfalls are to be of the order of 50 m to ensure significant dilution of the sewage plume in the near field. Ocean currents would then further disperse the sewage plume. Figure 1 shows schematically the layout of a typical tunnelled outfall.

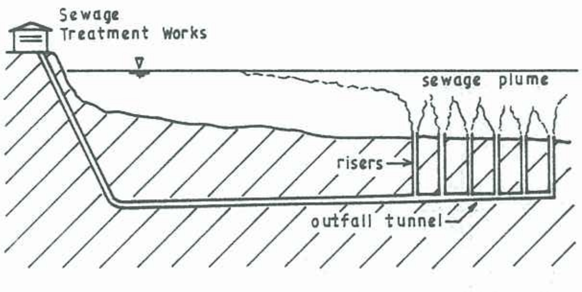

Figure 1 Schematic diagram of a tunnelled ocean outfall.

The sewage is carried from the tunnel up to the sea floor through a series of vertical risers and finally discharges into the ocean through diffuser ports located at the tops of the risers. The diffusers are designed with the intention of maximising the initial mixing and therefore the dilution of the sewage with the surrounding ocean water.

Tunnelled outfalls are preferred to sea bed pipelines on high energy coastlines as the problem of wave attack is then largely avoided. A number of tunnelled outfalls have been constructed in the United Kingdom and at least two of these, at Aberdeen and Weymouth, have not performed up to their designers expectations {Munro, (1981) and Charlton, (1982)}. Inspections of these outfalls by divers has revealed that no sewage is being discharged from the most seaward risers. Instead the sewage is being discharged from the shoreward risers and the anticipated dilution rates are not being achieved. Also pumping heads and therefore pumping costs are greater than expected.

The failure of these outfalls to function as originally designed has been attributed to the intrusion of sea water into the seaward end on the outfall tunnel. The sea water having a density greater than that of the sewage forms a wedge in the tunnel which may totally block off risers at seaward end of the tunnel as shown in Figure 2.

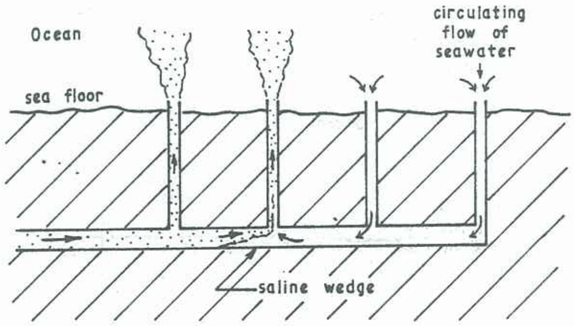

Figure 2 Saline wedge resulting from incomplete purging of a tunnelled ocean outfall.

Model experiments by Munro (1981) and Wilkinson (1983(a)) have shown that a sewage flow many times that required to prevent intrusion of sea water through the riser ports is required to purge sea water from the outfall tunnel. In the past, the design criteria for the ports has been to ensure that the densimetric Froude number of flow issuing from a single port exceeds unity. Jorg and Scorer (1967) showed that if the condition is met sea water is unable to intrude into the port. However the sewage flows required to satisfy this condition are generally insufficient to purge the outfall tunnel of sea water.

As most outfalls are initially totally flooded with sea water, purging can be a problem. Outfalls having risers which connect to the roof of the tunnel should be designed according to the purging criteria rather than that of saline intrusion at the ports. The latter condition will always be satisfied if the former criteria is satisfied. Wilkinson (1983(b)) has developed a theory which predicts the flow required to purge a tunnelled outfall of seawater as a function of the fluid densities and the tunnel geometry. The theory is well supported by experimental data.

The problem of purging the outfall tunnel can be much simplified if the risers are connected close to the invert of the outfall tunnel rather than at the roof. This geometry has been adopted for the San Francisco outfall, which is presently under construction, and will probably be adopted for the proposed Sydney outfalls. A cross-sectional view of this system is shown in Figure 3.

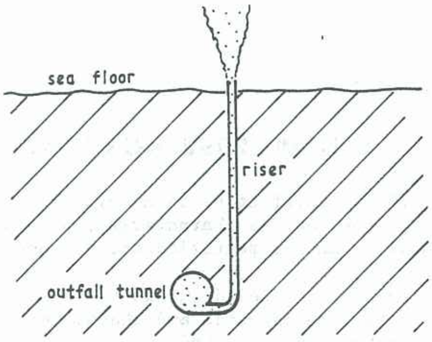

Figure 3 Cross-sectional view of an outfall geometry designed to avoid the formation of saline wedges.

Provided the sewage flow at start-up is carefully controlled, the sewage will lie above the sea water in the tunnel. As sewage continues to flow into the tunnel the sea water is displaced downwards into the risers and the tunnel is purged of sea water before sewage can enter the risers. Wedge formation is thus avoided. A schematic illustration of the purging of such an outfall is shown in Figure 4.

2 CIRCULATION BLOCKING

The following discussion is based on observations of the behaviour of a model tunnelled ocean outfall. Details of the model will be described in a later section.

The sequence of events which can lead to circulation blocking of the shoreward risers of a tunnelled ocean outfall are shown in Figures 5(a) and 5(b). When pumping of sewage into an outfall ceases, conditions in the tunnel are statically unstable and sewage contained in the tunnel is displaced by the denser surrounding sea water. The seaward momentum of sewage between the first (shoreward) and last risers causes dense sea water to intrude into the shoreward risers while the displaced sewage discharges from seaward risers as shown in Figure 5(a). A quasi-steady flow soon becomes established with the riser ports acting as internal hydraulic controls. Densimetric Froude numbers at the outlet ports are of order unity and velocities in the risers can be comparable (in magnitude not direction) with the normal design values. In a large outfall system, this displacement flow could continue for many hours following a shut-down. Mixing of the inflowing sea water with sewage in the tunnel increases the effective volume of buoyant fluid to be displaced and therefore the time this takes. If the sewage flow is restarted while the displacement flow continues, the momentum of sea water sinking down into the tunnel from the shoreward risers can overcome the buoyancy of the sewage and prevent it from entering those risers. The sewage is then carried down the tunnel to the more seaward risers which discharge it into the ocean as shown in Figure 5(b).

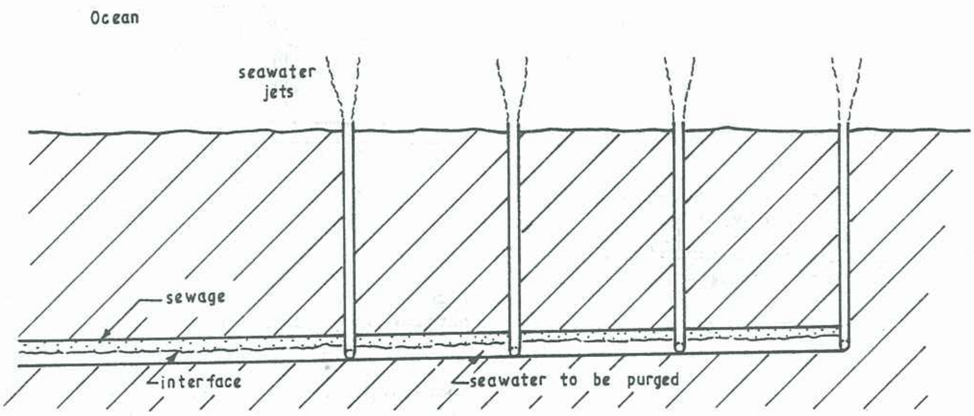

Figure 4 Connection of risers at the tunnel invert permits displacement of seawater from the tunnel before any sewage is discharged. This helps prevent wedge formation in the tunnel.

Unfortunately wedge formation is not the only mechanism by which risers can be rendered ineffective. Another mechanism, which will be termed circulation blocking, is described in the following section. Once established, purging of a riser subject to this phenomenon requires a sewage discharge comparable with that required to purge a wedge blocked outfall. Circulation blocking can only develop when attempting to restart sewage discharge from an outfall tunnel following a complete shut-down. Fortunately the phenomena can be avoided by careful programming of the start-up following a system shut-down.

Once established this circulation blocking of the shoreward risers is quite stable, and unless the sewage flow is increased to beyond a critical purging value, the blocked condition will persist indefinitely. It should be emphasised that circulation blocking can be effectively avoided by ensuring that quiescent conditions exist within the outfall tunnel before restarting the sewage flow. It is therefore desirable that flow monitoring be provided to detect fluid motion in outfall tunnels.

Circulation blocking can be stopped by purging an outfall however the flow required would generally well exceed the design flow for the system. This purging flow can be determined rather simply as shown in the following section.

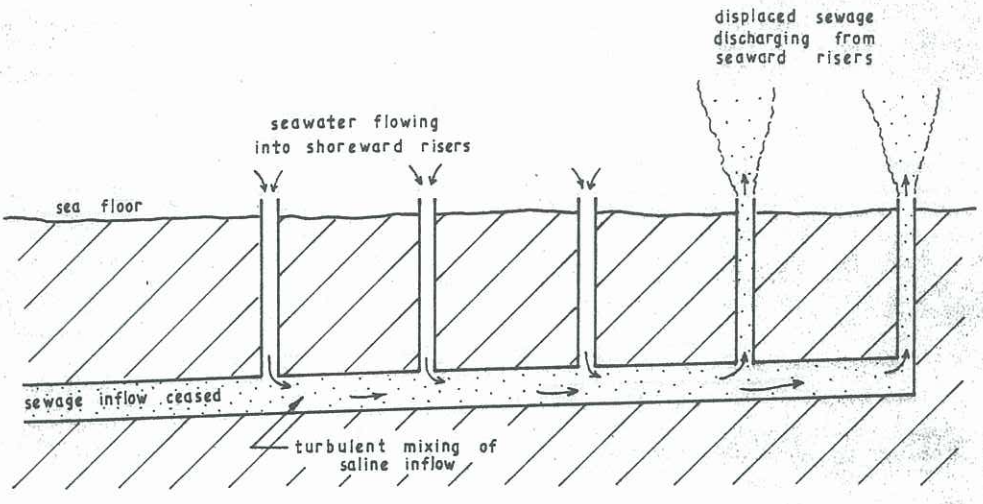

Figure 5(a) Circulatory flow established shortly after shut down of sewage flow into a tunnelled outfall.

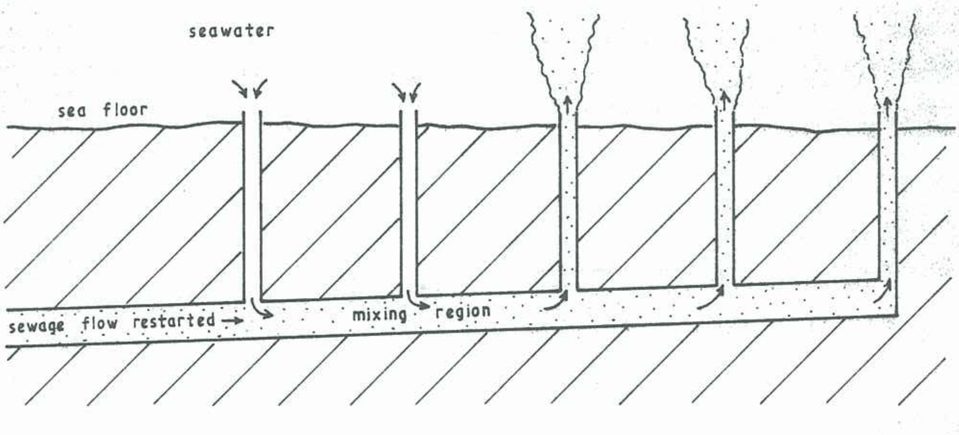

Figure 5(b) Circulation blocking of sewage flow from the shoreward risers caused by premature commencement of sewage discharge following a system shut down.

3 ANALYSIS

An expression is derived for the sewage flow required to purge a circulation blocked riser. The analysis is undertaken for the simplest possible system consisting of two risers. This is sufficient to obtain a quantitative feel for the relevance of the various parameters and the analysis can be readily generalised to cope with a more realistic system. A schematic diagram of the geometry to be analysed is shown in Figure 6.

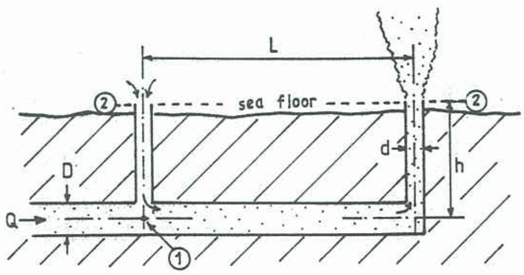

Figure 6 Schematic view of a circulation blocked riser.

Two risers of height h and diameter d connect to an outfall tunnel of diameter D a distance L apart. The direction of flow at base of the shoreward riser (1 in Figure 6) is determined by the magnitude of the pressure p_1 at the base of that riser. If p_1 is less than the piezometric pressure head of the fluid in riser 1, the flow in that riser will be directed downwards into the tunnel. Expressed symbolically this condition becomes

$$p_1 < p_2 + \rho g h$$

where p_2 is the pressure at the top of the risers and ρ is the density of the fluid in the riser. If a condition of circulation blocking exists then the pressure required at the base of the riser to nullify the circulation is given by

$$p_1 = p_2 + \rho_o g h \qquad (1)$$

where ρ_o is the density of the salt water in the riser. p_1 can also be related to the flow from the adjacent riser by employing the Bernoulli equation. This yields

$$p_1 = \frac{\rho_s}{2}(V^2 - U^2) + \rho_s g h + p_2 + p_f \qquad (2)$$

where V and U are the mean velocities in the riser and tunnel respectively and ρ_s is the sewage density. p_f is the pressure loss caused by frictional dissipation between the base of riser 1 and the top of riser 2. This may be expressed as

$$p_f = \frac{\rho_s V^2}{2}\left(f_T \frac{L}{D} + K\right) + \frac{\rho V^2}{2} f_R \frac{h}{d} \qquad (3)$$

where f_T and f_R are the Darcy Weisbach friction factors of the tunnel and riser respectively and K is the loss coefficient at the tunnel riser transition.

Equations 2 and 3 can be expressed in terms of the sewage discharge Q. The critical discharge Q_c required to relieve circulation blocking of the first riser is obtained by equating the two equations for p_1 to give

$$\frac{Q_c}{A(\Delta gh)^{\frac{1}{2}}} = \sqrt{2}\left[\left(\frac{D}{d}\right)^4 - 1 + p^*\right]^{-\frac{1}{2}} \qquad (4)$$

where p* is the normalised head loss and is given by

$$p^* = p_f \Big/ \frac{\rho_s U^2}{2} = \left(f_T \frac{L'}{D} + K + \left(\frac{D^4}{d}\right) f_R \frac{h}{d}\right) \qquad (5)$$

A is the cross-sectional area of the tunnel and Δ is the normalised density difference given by $\Delta = (\rho_o - \rho_s)/\rho_s$.

It is apparent from Equations 4 and 5 that the normalised critical discharge $Q_c/A(\Delta gh)^{\frac{1}{2}}$ reduces rapidly as the riser diameter (or specifically the effective diameter riser ports) is reduced. The critical discharge also reduces as frictional losses between Section 1 and 2 increase. These losses increase the pressure at the bottom of the first riser thereby retarding the flow of sea water down into that riser.

4 EXPERIMENTS

A series of experiments were conducted in the facility shown schematically in Figure 7.

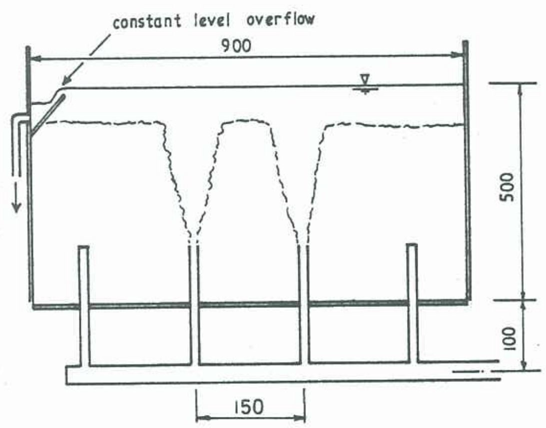

Figure 7 Schematic diagram of the experimental facility. Dimensions are in millimetres.

The outfall tunnel was modelled using clear P.V.C. pipe having an internal diameter of 25.4 mm. Four risers were provided and were used in the observational study where the various blocking mechanisms were identified, however in the quantitative experiments, two of the risers were blanked off.

The risers had internal diameters of 19.4 mm but this could be reduced to 15.1 mm and 12.2 mm by inserting sleeves into the risers. The insertion of the sleeves gave the values of the geometric parameters listed in Table 1.

TABLE 1

Riser diameter (mm)	h/d	D/d
19.4	11.6	1.31
15.1	15.0	1.61
12.2	18.5	2.00

Fresh water was used to simulate the sewage while the main tank into which the risers discharged was filled with brine. The normalised density difference Δ ranged between 1.2% to 2.8% in different experiments.

The aim of the quantitative experiments was to examine the validity of Equation 4 for the critical discharge required to clear a circulation blocked riser. For this reason the head loss between the base of the first riser and port of the second riser was measured directly from pressure tappings located at each of those sites. The difference in pressure was measured using simple manometers and a vernier sighting telescope which enabled $p_f/\rho g$ to be resolved to an accuracy of ± 0.2 mm. The normalised head loss was measured by this means for each of the three different values D/d and h/d given in Table 1 and are listed in Table 2.

TABLE 2

D/d	p*
1.31	4.3
1.61	6.6
2.00	16.0

These independent measurements of p* enabled an exact assessment of the validity of Equation 4 without employing fitting parameters.

The procedure followed in the experiments was as follows: The fresh supply was increased until the outfall was totally purged of salt water. The fresh supply was then shut off producing the circulatory flow shown in Figure 5(a). The fresh flow was then restarted producing the circulation block condition in the first riser. The flow of fresh water into the tunnel was slowly increased until the circulating saline flow stopped and fresh water discharged from both risers. Ten evaluations of the critical discharge were made for each riser diameter and the normalised critical discharge was calculated for each of the three values of h/d and D/d given in Table 1. The variance ratio of $Q_c/A(\Delta gh)^{\frac{1}{2}}$ ranged from 4% to 7%.

The mean value of the normalised critical discharge is plotted in Figure 8 against D/d for each of the geometries tested.

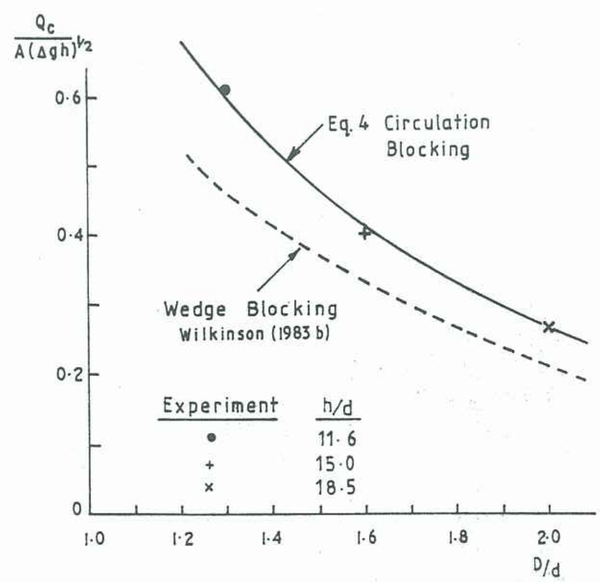

Figure 8 The normalised critical discharge as a function of outfall geometry.

It must be emphasised that specific values of h/d and p^* are associated with each value of D/d and these only apply to the geometries of these particular experiments.

Equation 4 is also plotted in Figure 8 using the independently determined values of p^*. Agreement between the theory and the experimental data is very close.

As a matter of interest, the dotted curve in Figure 8 shows the normalised critical discharge required to purge a saline wedge from the outfall tunnel as determined by Wilkinson (1983(b)). It will be noted that the sewage discharge required to clear circulation blocking of a riser is somewhat greater than that required to purge a saline wedge from the tunnel.

5 CONCLUSIONS

It has been demonstrated that if sewage discharge is restarted too soon following a shut down, a circulatory flow of sea water down the shoreward risers may develop thereby preventing the discharge of sewage from those risers. This phenomenon has been termed circulation blocking. Unlike wedge blocking of an outfall tunnel, circulation blocking cannot be prevented by modification of the tunnel-riser transition. However the condition can be avoided by ensuring that transient motions in the outfall tunnel have completely ceased before attempting to restart sewage discharge following a system shut-down. Alternatively the circulation blocking can be stopped by providing a sewage flow which exceeds a critical value. The means by which this critical flow may be determined is described in this paper.

6 REFERENCES

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