SALINITY INTRUSION INTO MULTI-PORT SEA OUTFALLS

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ABSTRACT

Sea water intrusion into the diffuser system of a long sea outfall is likely to reduce the efficiency of the outfall. Recent surveys have revealed outfalls with a significant proportion of their diffuser blocked, and others discharging through as few as 50% of their diffuser ports. It is suspected that intrusion is the cause of these malfunctionings. Intrusion may be encouraged by the design requirement of low efflux velocities to obtain optimum dilution, or by over-design to cater for future increases in discharge. Although intrusion can only commence at low discharge velocities, when a port Densiometric Froude number falls below about 1, once it has started sea water will continue to enter the diffuser system until a state of balance is reached. Subsequently a considerably greater flow will be required to purge the outfall of all sea water. Intrusion may also be prematurely triggered by wave action, currents, or by reduced flow through a damaged port.

Hydraulic model tests at the University of Dundee are leading to an understanding of the intrusion mechanism as it affects the various diffuser systems in current use. A continuing research and site survey programme is aimed at design recommendations to eliminate intrusion or reduce its effects.

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1. INTRODUCTION

Long sea outfalls are being increasingly used to convey waste effluents away from the coastline into areas of the sea where currents are able to generate conditions favourable to rapid dilution and dispersion.

Most of these outfalls terminate in some form of multi-port diffuser designed to optimise the initial dilution of the effluent. The main design criteria for a diffuser system are:-

a) that the flow through the ports should be as equal as possible over the full discharge range of the system,

b) that head losses should be kept to a minimum, and,

c) that the initial or rising plume dilution should be as great as possible.

This is generally achieved by designing for low diffuser port flow efflux velocities, the limit being that the port Densiometric Froude number should remain greater than unity. (At values less than unity saline reverse flow will occur). (Abraham 1963, Brookes 1970)

Outfalls are frequently designed to cater for future population growth and consequent future increase in discharge. By their very nature, they also have to cope with wide ranges of discharge, particularly if they carry storm water. Thus it is likely, especially in the early life of an outfall, that it will occasionally operate under low flow conditions which are favourable to sea water intrusion.

Unfortunately, out of sight, out of mind, has too frequently been the dictum of many operators of sea outfalls, and it is therefore not too surprising that reduced performance of an outfall is rarely reported. However a number of observations have recently come to hand indicating that some outfalls have not been functioning in the manner that their designers envisaged. Noticeable failure is apparently rare, but reduced performance surprisingly common. A notable example in the UK, recently reported, is that of the Hastings sea outfall (type b, fig. 1). It was discovered that, although the outfall had been discharging its full load, a substantial portion of the seaward end of the diffuser was blocked by debris and marine growth. It is now accepted that this blockage resulted from continuous sea water intrusion due to over conservative design. (Bennet 1981, 1982) A similar case has been reported in 1982. Another case concerns a large UK tunnelled outfall (type c, fig. 1) in which only half of the diffuser risers are carrying effluent at the design D.W.F.

The problem of sea water intrusion is not new, but the realisation of the problem is comparatively new. It was at the ICE Conference on Sea Outfalls in London in October 1980 that the problem was privately discussed by a number of experts. One of the main difficulties on this occasion was conceptual, in that nobody had observed the intrusion problem, and its manifestation was largely conjectural, although a number of outfall designers had proposed mechanisms for the intrusion process.

1.1 Pilot model

A thorough literature search yielded virtually no references on the subject and no record of any relevant outfall model testing. Therefore in an attempt to elucidate the problem, a pilot model of a tunnelled outfall was constructed in the hydraulics laboratory at the University of Dundee. This model, entirely constructed in perspex, had a foreshortened tunnel and only two risers. For a typical outfall its modelling scale would be about 1:20. Despite difficulties in maintaining appropriate salinity levels in its small 'sea tank', this model convincingly demonstrated some of the intrusion mechanisms, and that intrusion problems could arise in existing outfalls. The opportunity to observe the intrusion process was extremely valuable and necessary before we could attempt to quantify the process by a theoretical approach.

1.2 The Aberdeen outfall model

We were very soon able to apply the lessons learnt on the pilot model when the Grampian Region's Department of Water Services, through their consultants D. A. Donald and Wishart of Glasgow, commissioned the building and testing of a section of the Aberdeen sea outfall, which was then under construction.

The Aberdeen outfall comprises a landward shaft and a 2.5 km tunnel of 2.5 m diameter, the last 270 m of which is a diffuser section. Ten diffuser risers are connected to the tapering tunnel invert on alternate sides at 30 m centres. (type d, fig. 1) The shaft, some 40 m of tunnel and the first 100 m of the diffuser section including four risers was modelled in perspex, to a scale of 1:18.9. The risers discharged into a 6 m^3 'sea tank' maintained at a density of 1025 kg/m^3, and flow behaviour was observed with the aid of a comprehensive dye injection system.

This model has now been superseded at Dundee by a multi-purpose outfall test facility built on very similar lines to the Aberdeen outfall model. This facility has been financed by the UK Science and Engineering Research Council as part of a 3 years laboratory and site investigation into the salinity intrusion problem. (Charlton 1982).

1.3 Sea water intrusion as a design parameter

It has become evident that the traditional approach to sea outfall design needs to be modified taking into account an appreciation of the intrusion phenomenon. It will be another 3 years before an analysed description of intrusion processes can be published from the Dundee research programme, but in the interim period it is considered that a broad description of these processes as they have been observed to date would be beneficial to those currently engaged in outfall design.

While not attempting to supply the answers, the following sections of this paper describe the intrusion process, and its consequences, as a current 'state of the art' document.

2. OUTFALL DESIGN

The criteria listed in section 1.2 are generally achieved, after appropriate hydrographic and dispersion surveys (Charlton 1980), by conveying the effluent seawards through a pipeline or tunnel to a diffuser section which is designed to maximise the initial dilution. Invariably the diffuser section comprises a number of ports close to the sea bed. The number and spacing of these ports is a function of the water depth, total effluent flow and the required surface dilution. The use of the Brookes and Abraham rules results in low port efflux velocities and consequent low differential pressures between the outfall pipe and the sea, particularly at low discharges. Outfalls frequently operate over wide ranges of flow and in trying to obtain maximum dilutions over the higher flows, designers sometimes reduce port Densiometric Froude numbers very close to unity, when intrusion is likely to occur. It will be shown in later sections that intrusion under these conditions can be triggered by other factors at flows corresponding to significantly higher Densiometric Froude numbers.

Clearly, if an outfall is being designed to cater for increased loadings in later life, this problem is exacerbated.

3. OUTFALL TYPES

To list the many variations of outfall design would be superfluous, but to simplify matters we may divide outfalls with diffuser sections into four main types.

a) Sea bed outfall pipes with the diffuser section being entirely above the sea bed. In this case the diffuser ports are usually in the side of the pipe. Fig. 1 (a).

b) Shallowly buried outfall pipes, the diffuser section consisting of a number of short riser pipes. Fig. 1 (b).

c) Tunnelled outfalls where the diffuser section consists of a number of shafts connecting the soffit of the tunnel to sea bed diffuser heads. Fig. 1 (c).

d) Tunnelled outfalls where the diffuser section consists of a number of staggered shafts connecting the invert of the tunnel to sea bed diffuser heads. Fig. 1 (d).

4. THE INTRUSION CONDITION

4.1 The intrusion condition in an outfall with a diffuser section entirely above the sea bed (Fig. 2).

This type of outfall tends to be self regulating, the amount of sea water remaining in the pipe at any given time depending on the gradient of the pipe and the location of the outlet ports.

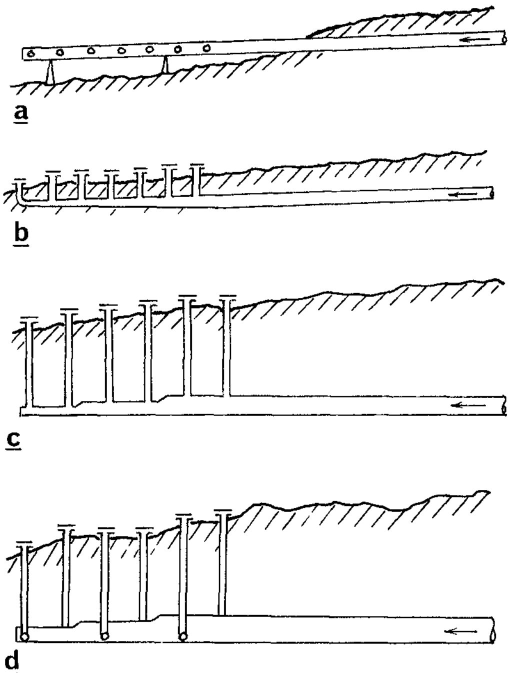

Figure 1 The four main types of outfall and diffuser configuration

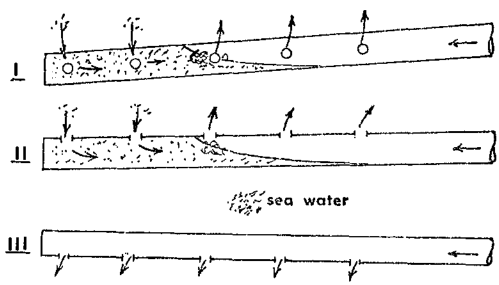

Figure 2 Intrusion processes in type a outfalls

Figure 2I shows how sea water intrudes into an inclined diffuser section. A similar interface configuration will occur whether the ports are on the side, top or bottom of the pipe.

The fresh-saline water interface will move downstream with increasing flow and vice-versa until an equilibrium position is reached. Mixing at the interface will be replenished by inflow through the sea water submerged ports.

As the diffuser pipe approaches a horizontal configuration there is a marked difference in performance between a diffuser with ports in the top or base of the pipe. (Figs. 2II and 2III) With top opening ports the flow patterns will be similar to case 2I, but with bottom ports there should be equal flow out of all ports at all times, particularly at low flows. (Any sea water within the pipe will be expelled with a horizontal interface inside the pipe until all sea water is cleared.)

4.2 The intrusion condition in a sea bed outfall with short vertical risers (type b), or a tunnelled outfall with longer risers (type c) both joined to the pipe/tunnel soffit.

These two cases are geometrically similar, the main difference being in the length of the riser pipes. (Fig. 3)

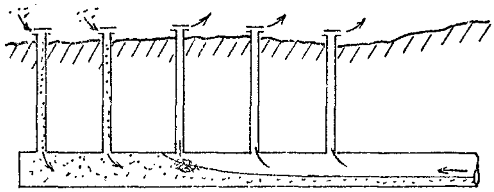

Figure 3 Intrusion process in type c outfalls

In this case the intrusive condition is very similar to that depicted in Figure 2II. However, the differential head created between a long riser full of sea water and another full of fresh water (effluent) increases with length and can generate considerable downward flow in those risers full of sea water. For equilibrium, mixing must take place at the interface as shown. Once again the interface will move to an equilibrium position.

4.3 The intrusive condition in a tunnelled outfall with invert connected risers.

This is the configuration that, to date, has been most closely studied (in the Aberdeen sea outfall model). (Fig. 4)

In this configuration the interface wedge is not so pronounced. The interface tends to form horizontally with a mixture of fresh and sea water being fed into the upward discharging risers. Under intrusive conditions some of the risers are full of sea water and flow downwards, thus maintaining the sea water layer in the tunnel.

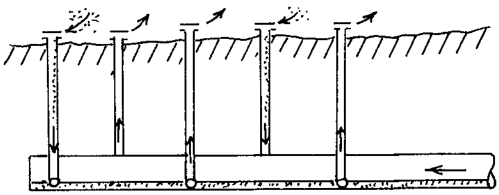

Figure 4 Intrusion process in type d outfalls

5. THE INTRUSION PROCESS

The conditions described in section 4 may be regarded as steady state conditions for a constant discharge. To arrive at this condition we may consider an outfall system full of sea water. This is a condition that would result from a cessation of effluent flow. If now a low flow of effluent commences, this flow will displace sea water with a clearly defined interface similar to that depicted in Figs. 2, 3 and 4. This interface will move downstream in types a, b and c with increasing effluent flow until the flow, and pressure differential, between the pipe and sea, is great enough to expel all the sea water. Once this condition is reached flow may be decreased again considerably before intrusion once again occurs. Intrusion will not recommence until the Densiometric Froude number of any orifice is reduced below unity. (See later for modifications to this condition.)

In the case of a type (d) outfall, with increasing flow from a fully saline start the horizontal interface in the tunnel is depressed until a mixture of sea and fresh water flows up the risers. At this stage, imbalances occur between adjacent risers and some actually go into reverse flow. This reverse flow maintains the saline layer in the tunnel and the upward flowing risers carry a mixture of fresh and saline water. With increasing effluent flow more risers come into the upward discharging state until eventually all are in this state and all sea water is expelled from the tunnel. As in the previous case intrusion cannot recommence until the outlet port Densiometric Froude Number reduces below unity. Once intrusion starts, it progresses to the full equilibrium condition described in section 4.3.

Flushing, which clears intrusive salt water with increasing fresh water flow tends to be a slow process as it depends on sea water entrainment by the fresh water, and there may be large volumes of sea water within the system.

Thus in most outfall configurations the intrusion process takes the form of a hysteresis loop, with an established intrusive condition persisting to fairly high flows, but once cleared, not starting again until a very low flow occurs. This is illustrated in Figure 5 where the total head loss through the outfall system is plotted against the total discharge. With intrusion the head required to discharge a given flow through a reduced number of ports is greater than it is without intrusion and discharge through all the ports.

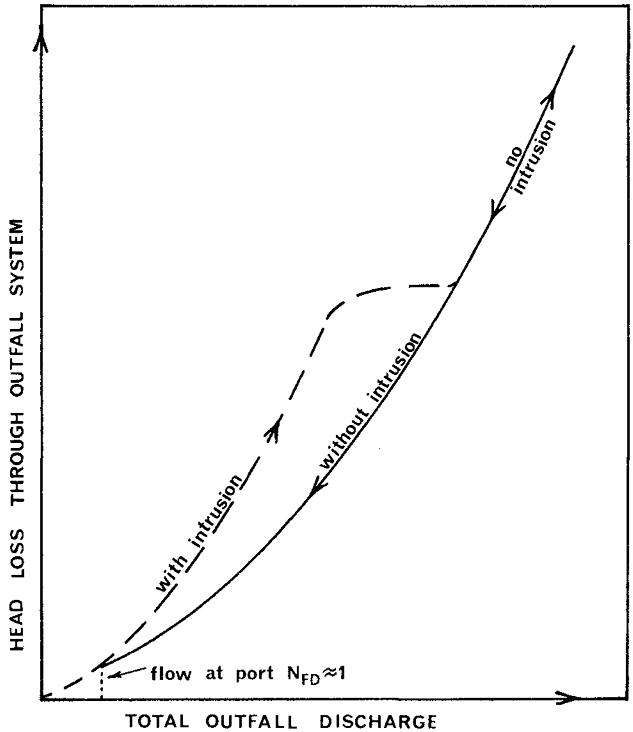

Figure 5 Diagram showing the effect of sea water intrusion on the head loss in a complete outfall system.

A number of factors may raise the commencement of intrusion above the nominal Densiometric Froude number unity condition. Wave action generating attenuated sea bed pressures will trigger this process, and varying levels of outlet port (usually due to sea bed slope) will generate unequal flows in tunnel diffuser risers at low flows. This latter condition will prematurely lower the flow in some outlets and make them vulnerable to intrusion.

6. THE SUSCEPTIBILITY OF OUTFALLS TO INTRUSION

By their very nature all outfalls are susceptible to intrusion to some degree at low flows. However some designs are more resistant than others. For example the configuration in Figure 2[illegible] is almost proof against intrusion. Types b and c have proved to be most vulnerable as the flow needed to expel all sea water is often very close to their maximum discharge.

Outfalls which operate over a wide range of discharge can be designed to function above the intrusive condition, and outfalls which operate at high efflux velocities are naturally protected.

7. THE CONSEQUENCES OF SEA-WATER INTRUSION

If intrusion and sea water clearance take place regularly due to cyclic flow variations, little harm will come to an outfall system. It is expected that a large number of outfalls operate in this fashion. However, if the clearance condition is only occasionally reached and intrusion persists for long periods, those areas of an outfall which contain sea water may become subject to marine growth and debris collection. This can eventually lead to blockage.

Often tunnelled outfalls are driven up-hill in a seaward direction for ease of construction drainage. When working under intrusive conditions stratified sea water will migrate downhill towards the landward shaft and obstruct the stratified fresh water flow. Sedimentation will thus be encouraged in the tunnel.

8. CONCLUSION

While saline intrusion may often occur in outfall systems, it may not be persistent and by its self regulating nature may go unnoticed. However, there are many outfalls whose performance is being restricted by the phenomenon.

This paper, while not giving the remedies, does aim to describe the intrusion process, in the belief that for designers an awareness of a problem is nine tenths of the solution.

When our current research programme is completed we hope to present working design criteria and designs that will enable designers to avoid, or minimise, problems that might be caused by saline intrusion.

Most of the observations made in this paper have come from hydraulic model investigations. While intrusion models are a new venture the principles on which they are operated are well proven, and prototype predictions based on their performance can be taken with confidence. We also have sufficient prototype case histories to back this confidence.

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