CHAPTER 77

EFFECT OF LOCAL CONDITIONS ON EFFLUENT DISPOSAL IN COASTAL WATERS.

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INTRODUCTION

Since 1957 the Civil Engineering Department of the University of Strathclyde has been engaged on basic and ad hoc studies in the field of Marine Technology. These studies have included problems of heat dissipation from the cooling water of very large power stations of capacities up to 2400 M.W. discharging 3200 cusecs at 7.5°C above ambient temperature sited on the sea coast or on estuaries, and problems of disposal of industrial wastes including highly toxic chemical wastes and pulp mill effluent.

A number of these problems have been amenable to treatment by hydraulic models and a great deal of the basic research of the Department has been concerned with investigations into model scaling laws, complementary field work being carried out from the Department's research vessel.

The paper describes some of the work in hand and the general approach of the group to the problems.

THE NATURE OF EFFLUENTS

The water-borne constituents of any effluent may be divided into two types; those causing deleterious effects and those whose effects on the receiving water are harmless.

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This distinction is a very rough one since deleterious effects are entirely dependent on the concentration of the substance. A further subdivision may be made by classifying the deleterious constituents as conservative and non-conservative. A conservative constituent is one which although it may undergo biological, physical and chemical changes with time in the receiving water, retains its deleterious character. Examples of conservative constituents are metallic ions from trade wastes, chlorinated hydrocarbons from pesticides, both of which can be toxic to marine life. Even where the initial concentration is non-toxic these chemicals can be retained by organisms and built up to concentrations which are toxic or render the organism toxic. Another important example is 'hard' synthetic detergents which have the effect of cutting down the free surface oxygen transfer rate by a considerable amount; a reduction of 50 percent has been reported in certain estuaries.

Non-conservative constituents on the other hand undergo biological, physical and chemical changes with time in the receiving waters which render them innocuous or even beneficial, e.g. nitrogen, phosphorous. However, these changes may introduce effects which are deleterious, as for example the oxygen uptake of organic and of some inorganic substances, which may reduce the oxygen level to such an extent that marine life suffers or anaerobic conditions are set up.

The very fact of heating of water, which is drawn from an estuary and returned there without other change, can make the outflow analogous to an effluent with a deleterious but non-conservative constituent. The major contributions here come from power station cooling water systems, and the quantities involved can be considerable, for example Longannet Generating Station will discharge some 3200 cusecs at about 8°C above ambient into the upper estuary of the River Forth in Scotland at a point where a heat barrier to migratory fish could possibly occur. A hydraulic model study showed that such a barrier could occur but that the forecast recurrence period was on two daytime tides in 10 years, and only if the station had run at full load for several weeks of summer weather.

The problem of the engineer is to design and site the outfalls in order to minimize costs of treatment. In general he is required to meet certain standards as to the concentration of deleterious substances and the allowable oxygen sag. Often, especially in open waters, these standards may be relaxed in the immediate vicinity of the outfall allowing the required standards to be met wholly or partly by dilution processes, within the receiving waters.

It is necessary for very thorough hydrographic studies to be carried out in such an area. These studies can, in themselves, be very difficult to interpret. For example on the West Coast of Scotland with its fiordic sea lochs it is necessary to calculate the retention half life of a particle of sea water entering the system in order to calculate the oxygen balance of the system or the build up of a conservative tracer. A system may consist of three basins connected by shallow tidal channels. Tracer techniques are not very helpful, because in general the volumes of the systems are so vast that the amount of tracer required to give an answer of value would be uneconomic. However, the inflow of fresh water to the lochs can be utilised as a tracer and results obtained can be used to predict the gross effects of an effluent. The local effects present a much more difficult problem since the method of introduction of the effluent may affect the local hydraulic regime considerably and in areas of weak currents may even dominate it.

INITIAL DILUTION

Discharge of troublesome effluents into estuaries and coastal waters has been the accepted practice of the majority of coastal towns and industries in the United Kingdom for many years. With greater recreational use being made of these waters, their misuse is turning the weight of public opinion against allowing the present practice to continue. Not only is the total quantity of effluent increasing but the scale and volume of some of these effluent discharges are comparable with those experienced in nature. Discharge of the effluent to the receiving water generally takes one of the three following forms:-

(a) Free discharge over a foreshore or beach
(b) Discharge into or by a dredged channel
(c) By submerged outlet.

In case (a) the effluent either disperses itself over the beach in a fan or erodes a channel for itself down the foreshore. In both these methods the effluent is introduced comparatively smoothly to the receiving water, and if its density is less than that of the receiving water, the effluent may spread with a minimum of turbulent mixing. Should there be no density difference the effluent displaces the receiving water until eroded by local currents. Thus minimal dilution of the effluent has been brought about by its mode of entry into the receiving waters and further dilution is dependent on turbulent diffusion, and where applicable, on densimetric spread processes.

Case (b) is similar to case (a) in that effluent is injected comparatively gently.

Where the outlet is submerged as in (c) considerable entrainment of the receiving water may take place into the plume formed by the introduction of the effluent thus offering considerable dilution close to the point of discharge. This may be particularly valuable where the effluent contains toxic conservative pollutants. The theory of buoyant and non-buoyant plumes or jets and the design of diffusers - multiple jets - has been dealt with extensively in the literature by Rawn, Bowerman and Brooks[1] Pearson,[2] Abraham[3] and others but little has been described of the effects of local conditions.

Discharge is seldom made into quiescent water and the relative velocity of the receiving water can have a major effect on the behaviour of the plume and also on the effectiveness of a diffuser system. From preliminary small scale laboratory experiments with a buoyant effluent it was observed that in all cases dilutions at the surface were greater than those obtained in quiescent water, the greatest dilution being obtained when the discharge was directed into the current. If however the discharge was directed downstream and the speed of the receiving waters great enough, the plume can be held near the sea bed with no unpolluted water below it, thus permitting no entrainment from below. In this case a vertical plume gives a much better dilution at a selected section downstream of the discharge. In the case of a toxic effluent, the choice of a vertical plume could also prevent sterilisation of the sea bottom in the vicinity of the outfall. The behaviour of the flow of the receiving water round the discharge pipe in a diffuser system can play an important part in the behaviour of plumes from a horizontal discharge especially when the pipe is just raised off the sea bed.

In a multi-discharge installation the plumes may merge into one another, cutting down the effective dilution if the ports are not far enough apart. This condition may be worsened if the currents in the receiving water are not parallel to the axis of the discharge, i.e. normal to the main pipe.

Where a buoyant effluent is discharged into a stratified system, the presence of a layer of relatively fresh water on the surface of the receiving body of water may not necessarily prevent the effluent reaching the surface. Although dilution calculations may indicate that an effluent density in excess of the upper layers is attained before reaching the surface, the upward component of momentum can in many cases carry the plume through the stratification interface. On reaching the surface the greater density of the effluent will again predominate causing the more dense water to sink to an intermediate level.

In shallow water care must be taken to ensure that currents are adequate, or that the densimetric spread rate is sufficient, to carry away the effluent without the surface layer thickening, thus preventing diluting water from inflowing along the bottom so as to be entrained into the plume without previous contamination.

HYDRAULIC MODEL EXPERIMENTS

The hydraulic model experiment represents the ultimate attempt to make allowance for local configurations. However, the first step in obtaining a basis of design is to observe examples of a relevant flow phenomena in idealised conditions. These observations should ideally encompass the order of scale of the prototype and of possible models.

From the buoyant spread of an effluent, the analogous circumstance which has been adopted is lock exchange flow in a wide channel.[4] Fig. 1 shows lock exchange flow schematically. A somewhat simplified functional equation for the time of travel, T, of a front over a distance L is:

$$\frac{T}{\sqrt{\left\{\dfrac{H}{\left(\frac{\rho_s-\rho}{\rho}\right)g}\right\}}} = \phi\left[\frac{\left(\frac{\rho_s-\rho}{\rho}\right)^{\frac{1}{2}} g^{\frac{1}{2}} H^{\frac{3}{2}}}{\nu}\ ,\ \frac{L}{H}\right] \tag{1}$$

where H is the depth of the flume, ρ_s is the density of the water on one side of the barrier in Fig. 1 and ρ is the lesser density of the water on the other. The acceleration due to gravity is represented by g and the kinematic viscosity by ν. For various reasons the plot given by Eq. (1) and shown in Fig. 2 has now been adopted in place of Keulegan's congruency diagram which had been previously used [4] to present this type of data. A flume built especially for the work has allowed observations to be made at much greater values of $F_\Delta R = \left[\left(\frac{\rho_s-\rho}{\rho}\right)^{1/2} g^{1/2} H^{3/2}\right]/\nu$ than previously. This flume is 290 feet long, 5 feet wide and 16½ inches effective depth.

At the other extreme some of the results shown on Fig. 2 were obtained in a quarter inch deep flume using 50:50 sugar water solution as the basic fluid, the density difference again being obtained with salt. The consistency of the results is extremely satisfactory, and the diagram clearly demonstrates the onset of Froudian similarity at higher values of $F_\Delta R$. This latter feature is analogous to the onset of fully developed turbulent flow in a rough pipe with increasing value of Reynolds number.

Now suppose one takes an example of lock exchange flow with a value of $F_\Delta R$ of 10^6. Fig. 2 shows that a relative distance of 215 is travelled by the underflow in a non-dimensional time of 500. There has been some extrapolation to reach $F_\Delta R$ of 10^6 but inspection of the diagram shows this to be justified. It is now decided to operate a 1/500 scale model. A further restriction is imposed that $(\rho_s-\rho)/\rho$ in the model is to be the same as that for the prototype - the restriction which would be in force in a tidal model where simulation of the celerity of surface disturbances is a pre-requisite to simulation of spread depending on both currents and differential movements.

The value of $F_\Delta R$ is divided by $500^{3/2}$ giving a model value of about 100. At a non-dimensional time of 500, the relative travel of the underflow is 16. This represents a condition of completely unacceptable scale effect, and the adoption of vertical exaggeration is the necessary compromise. The exaggeration e is defined as x/y where 1/x is the horizontal scale and 1/y is the vertical scale. A solution must be sought where a L/H of 215/e is reached at a non-dimensional time of 500/e and at a $F_\Delta R$ value of $10^6/(500/e)^{3/2}$. By trial and error a value of 8 is found to come close to a solution - a relative extension of 25 at a non-dimensional time of 62.5 is given by a $F_{\Delta}R$ value of 2000, compared with a desired extension of 27.

To apply the method to an actual model design it is necessary, firstly, to assess the probable magnitude of the spread phenomena in the prototype and hence allocate a $F_{\Delta}R$ value, and secondly to determine a critical period of time on which the design is to be optimised. The example given is applicable to a large power station discharging heated effluent where a period of about one hour has been considered the design condition. There is, then, a considerable element of experience and skill still necessary in using the method. A general estimate of conditions is made, in particular the typical depth of front and hence the equivalent H, and the model is then designed and operated. From the results of the model the initial estimate is confirmed - or otherwise - and if the estimate is reasonably confirmed the results from the model give a detailed prediction of prototype conditions.

Fig. 2 actually deals with the progress of an underflow front. However from preliminary assessment of comparable results for overflow fronts, it can be said that the same Froudian condition certainly occurs at high values of $F_{\Delta}R$. The problems commonly studied in models are related to overflow fronts, and the difficulty in obtaining consistent overflow front results at low values of $F_{\Delta}R$ is an indication of the necessity to choose sufficiently large horizontal scales for models so that model values of $F_{\Delta}R$ in the region of 2000 or higher are obtained without undue vertical exaggeration.

A preliminary assessment of observations of the progressing fronts also indicates that simulation of the mechanism of spread found with the prototype Froudian conditions depends on keeping the corresponding model spreads within the Froudian limits - which is what the example given, in fact, does. If this is done, the spread mechanism maintains undiluted water at the front, the diluted water formed at the front being discarded and replaced by water moving forward at a greater velocity than the overall celerity of the front.

The introduction of vertical exaggeration cannot but cause local distortion at inlet and outlet points. The authors believe, however that in the typical circumstances of the surface spread of a buoyant effluent, the buoyant spread effect is dominant over the jet mixing effect. What happens is that the introduction of exaggeration does not affect the jet action which in a typical case may persist for, say, six length measures, where the length measure is the depth of water near the outfall. Interest may be in the travel of the front at distances of the order of 50 to 100 length measures away from the outlet, and the authors have found that the adoption of a small margin of safety is a sufficient step in some cases.

The alternative is to operate natural scale models of the vicinity of outlet and of the intake. Then arrangements are made that a flow of the correct dilution is initiated at the correct point in the vertically exaggerated model, data being gained from the outlet model. In turn data from the vertically exaggerated model is applied to the inlet model.

The procedures outlined above have been adopted in whole or in part for investigations concerned with the following generating stations sited on the estuaries of the Forth and Clyde.

Methil	120 MW	- 120 ft.^{3}/sec.
Cockenzie	1200 MW	- 1340 ft^3/sec.
Longannet	2400 MW	- 3200 ft^3/sec.
Hunterston	1200 MW	- beside existing 360 MW.

MODIFICATION OF SPREAD

The overall dilution of an effluent by the receiving water may be considered as comprising a number of distinct mixing processes occurring in different zones. Initial dilution has already been discussed in some detail. Where a density difference persists the final disposition of the diluted effluent will take the form of a stratified layer. In the majority of disposal problems this layer will be lighter than the receiving water and will thus form a surface 'raft' which in the absence of currents or other external agency, will spread radially from the point of discharge. The rate of spread and the dilution due to mixing at the front will depend on the density difference and the volume rate of flow, and as described in the preceding section, correct simulation of spread is of paramount importance in designing the exaggeration to be adopted in a model. In practice, the radial pattern of spread will be distorted as a result of tidal currents, waves and wind to name the three principal actions, and it is often the purpose of field and model investigations to study these factors with a view to determining an acceptable position for the point of discharge. Three of the aforementioned models designed to study thermal circulating water systems have included the effect of tidal flows, and in one of these the effect of a pronounced horizontal salinity gradient was successfully simulated and shown to be of considerable importance. In none of these models however, has an attempt been made to simulate the effect of wind and/or wave action and in anticipation of this requirement, some experiments have been initiated to study the problem in a simple two dimensional, idealised situation. The preliminary results of this work have already been presented by one of the authors[5] and work is currently continuing on this topic.

An important distinction must be drawn between the effect of tidal flows in which the receiving water has a fairly uniform velocity distribution over a considerable proportion of the depth, and the effect of wind and/or wave action whereby a surface velocity is imposed on the receiving water with a pronounced velocity gradient. The latter may be due to the mass transport of deep water($L/h \not> 2$) waves or to the shearing action of the wind and affect a layer of thickness of the same order as the stratified layer.

When no pronounced velocity gradient exists at the surface of the receiving water (as in tidal flow effects) the spread of a buoyant effluent may be taken as the vectorial sum of the spread velocity of the front and the tidal current. The technique of obtaining the correct exaggeration in order that the rate of spread in a model is correctly simulated has already been discussed in detail.

If surface drifts are produced by wind/wave action, the effect on rate of spread is, however, no longer simple. The mechanism within the layer of less dense fluid consists of a circulation pattern by which the front is constantly fed by undiluted water, balanced by a return flow at the interface. In this way the water entrained by the front is distributed along the interface forming the intermediate mixed layer. If an external agency superimposes a velocity gradient, which augments this circulation pattern, the progress of the front will not be increased dramatically. Instead, the shape of the front may be distorted and in all probability the capacity for the front to extend will be increased. The converse is true if the imposed velocity gradient opposes the circulation pattern within the layer. The front will be blunted but as long as some undiluted water continues to feed the front it will continue to advance at a rate not significantly less than the basic densimetric spread velocity. If, however, the imposed velocity gradient is strong enough to reverse the circulation pattern, the progress of the front will not only be halted, but a progressive breakdown of the layer will ensue until the front is replaced by a relatively extended zone within which there is a gradual horizontal transition from the effluent reft to receiving water.

The phenomena described are easily observed in small-scale two-dimensional idealised experiments, but the interaction of spread mechanism and surface velocity gradients is less easily studied in the field. One observation of interest was however obtained during the study of a warm water plume from a power station. Temperature traverses were made across the plume which was moving roughly parallel to the coast and it was found that the warmer water was deeper on the shore side by several feet. It is thought that this was possibly due to the presence of an on-shore surface drift but no quantitative data concerning phenomena of this kind have yet been obtained.

The point which emerges from these observations, which it must be emphasised, are still at a preliminary stage, is that correct simulation of both the density layer and the imposed velocity gradient is essential if the effect of wind and waves on the spread of front is to be correctly simulated. It is quite inconclusive to simulate only the wind or wave effect and assume that the effluent will behave in the same way as a tracer such as dye or floating particles.

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REFERENCES

1. Rawn, A.M., Bowerman, F.R., and Brooks, N.H. "Diffusers for disposal of sewage in sea water," Trans. ASCE, Vol. 126 Pt. III 1961 p. 344.

2. Pearson, E.A. "Submarine waste disposal installations," Proc. 6th Intern. Conf. on Coastal Engineering, December 1957.

3. Abraham, G., "Jet diffusion in liquid of greater density," Trans. ASCE, Vol. 126, Pt. I, 1961 pp 77.

4. Barr, D.I.H. "Densimetric exchange flow in rectangular channels I - definitions, review and relevance to model design," La Houille Blanche, No. 7, November 1963, pp 739-756.

5. Smith, A.A., "The effect of gravity waves on the spread of an effluent," Proc. XI Congress Intern. Assoc. for Hydraulic Research, Leningrad, 1965.

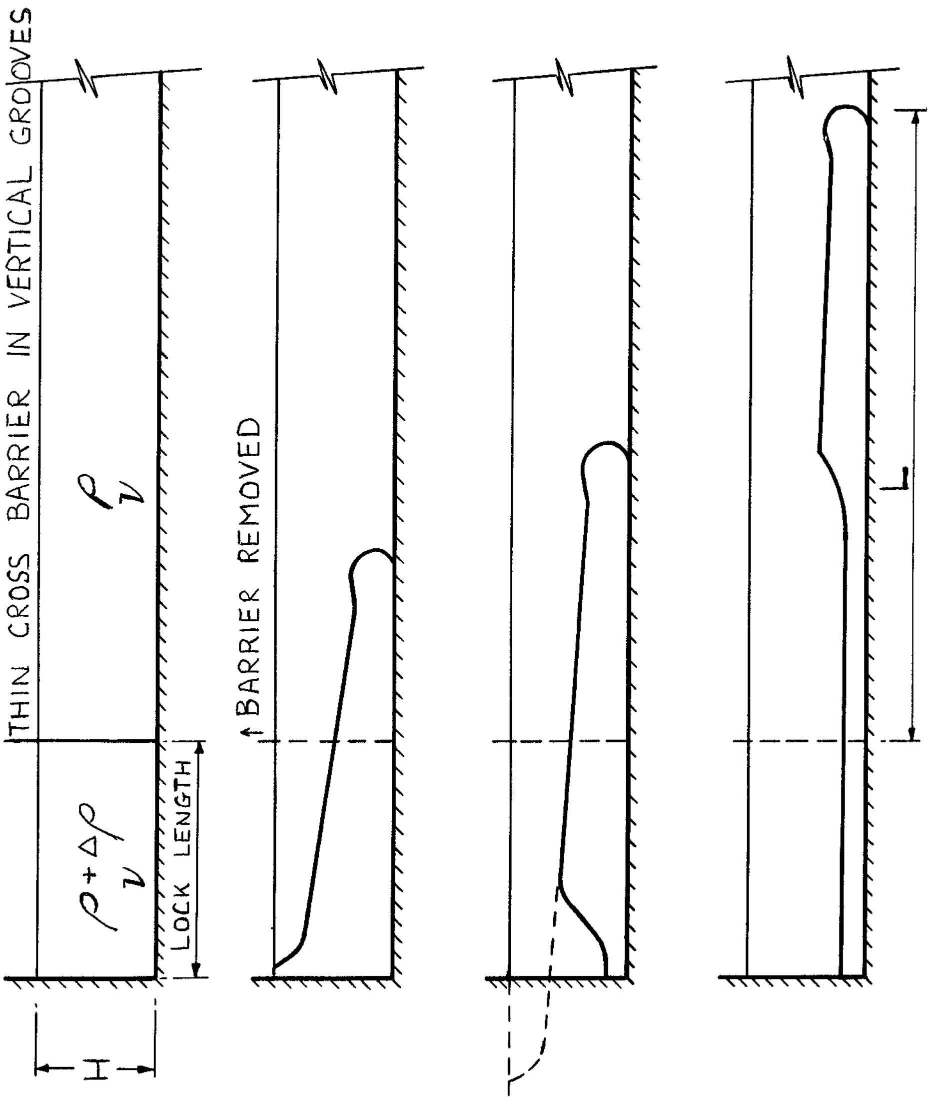

Fig. 1. Lock exchange flow - overflow reflected.

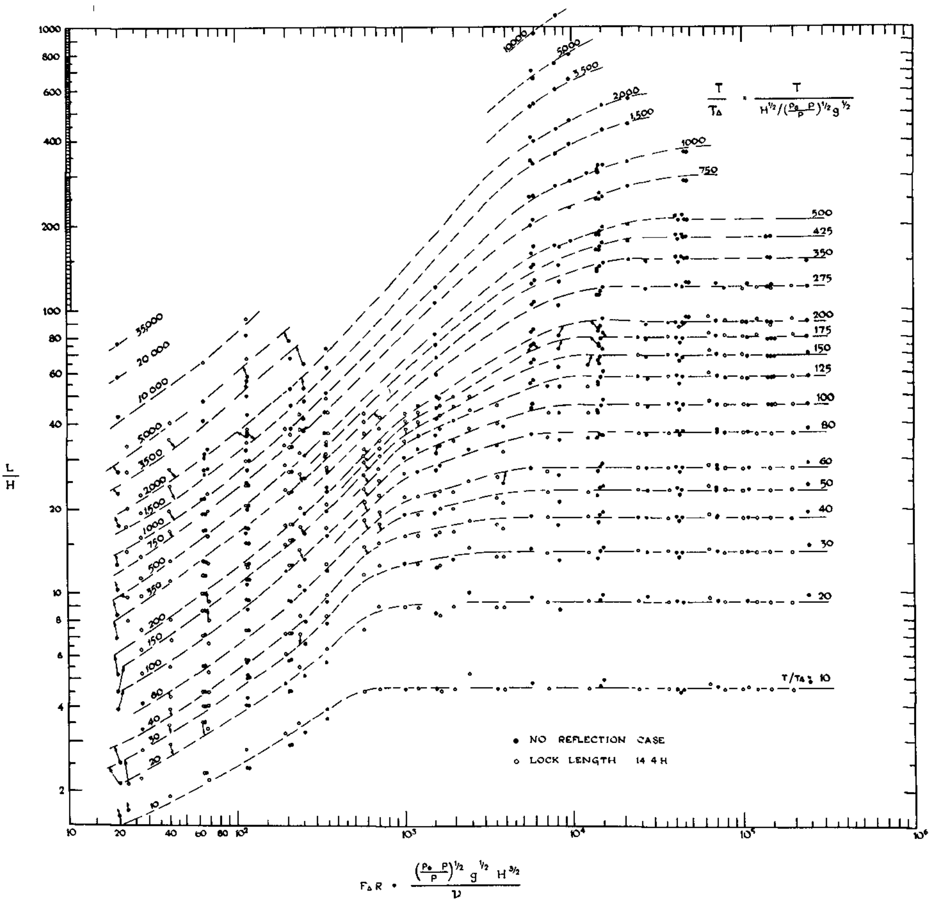

Fig. 2. New congruency diagram.