CHAPTER 354

THE EROSION OF A SALT WEDGE TRAPPED BEHIND A BARRAGE ACROSS AN ESTUARY

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Abstract

The problems associated with the stratification of fluids, particularly in estuaries, are of growing concern. Based on water quality problems which occurred at the River Lagan, N. Ireland, an experimental investigation was undertaken into the fluid mixing process within a stratified flow. High quality temporal measurements have been used to examine the processes of erosion of a saline stratification trapped behind a barrage. Two distinct mechanisms of wedge erosion have been identified, both of which involve the formation of a mixed layer.

Introduction

Density stratification in fluids occur due to variations in momentum, temperature and salinity. Mixing between such strata plays a critical role in various phenomena of meteorology, hydraulics and oceanography. Barrages are now frequently used to improve the visual appearance of estuaries by controlling water levels in a semi-tidal impoundment. In such impoundments fresh river water and salt water from the sea normally mix. However, under certain circumstances a stable stratification occurs between the two fluids. When the flow in a river is low, there is little mixing and therefore limited transfer of oxygen between the fresh and salt water layers. This can lead to oxygen depletion and possibly anaerobic conditions at the bed, with subsequent damage to the aquatic environment.

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Background

Belfast developed along a tidal reach of the River Lagan and many industries were established along the banks of the river. At low tide extensive areas of unsightly mudflats were exposed and so a weir was constructed across the river in 1934 to create, on part of the river, a semi-tidal pond which would cover the muds at all tide states. However, the construction of this weir led to periodic water quality problems. During periods of low river flows, the fresh and saline waters entering the pond from the river and the tidal flow stratified, and there was little flushing of the denser saline water trapped behind the weir. The oxygen content of the trapped water was rapidly depleted by the decomposition of organics in the water and the bed muds. This damaged the fish and plant life in the river and led to the produetion of hydrogen sulphide.

The demise of riverside industries and the poor river water quality resulted in the city turning away from the river front which rapidly became polluted. The result was that extensive inner city areas were blighted and had little development potential.

In 1969 the construction of a new weir downstream of the Queen's Bridge was proposed to regulate river levels and create an attractive water environment. This proposal was renewed by the River Lagan Working Group in the 1970s and specialist studies were instigated. In 1988, the Civil Engineering Department of The Queen's University of Belfast was commissioned to undertake a study seeking to establish design parameters for a structure which would control the water levels, protect the city against tidal flooding and improve the water quality in the river. The proposed impoundment was just under 5 km. in length with a surface area of 40 ha. This pond would have river flow and urban drainage inputs, some of which would have high biochemical oxygen demand levels.

Research Programme

A research programme was undertaken in which a physical model of some 8 km. of the tidal channel and harbour area, including the proposed impoundment, was constructed to a horizontal scale of 1:150 to establish design and operation parameters for the weir. A scale distortion factor of three was used to ensure adequate depths for the study of salinity profiles in the model.

In conjunction with the construction of the physical model a monitoring programme was established on the River Lagan. Velocity and salinity measurements were taken at a number of stations on the river for use in calibrating the model. The measurements were taken for river conditions ranging from low to flood flows, and at a variety of tidal conditions. The velocity measurements were used to establish boundary roughness values in the model at different water levels. The model was then validated by reproducing salinity profiles measured in the river at different tide states.

Salinity profiles at high tide, established after a number of tide cycles in the model, behind the existing weir showed that for a river flow of 2 cumecs the stratification was well defined and extended over the full length of the impounded reach. When the river flow was increased to 5 cumecs, the entrapped wedge retreated showing a significant reduction in both volume and concentration. A new weir placed at the proposed downstream site resulted in a pond with characteristics similar to that behind the existing weir. This showed that the construction of a fixed crest weir at the new site would simply replicate the problems of water quality being experienced behind the existing weir.

An active weir design was considered whereby the impoundment would be controlled by a gated weir structure incorporating a system for withdrawal of water at a low level. A gated weir would have the added advantage of being able to exclude high tides as well as controlling water levels in the impoundment. It was decided to use a gate system which would be able to exclude surge tide levels above that which would be reasonable expected at present but which might occur if the was a rise in tide levels due to global warming.

A low level withdrawal system was included to evacuate saline water from behind the weir on an ebb tide, when stratification problems were present in the impoundment. On a flood tide, the weir would allow saline water into the impoundment over the lowered gates. At high tide, the gates would be raised and the low level withdrawal system would be opened. This would allow drawdown of the impoundment, during the ebb tide period, through the low level withdrawal system which would have a capacity of 25 cumecs.

It became clear from the model study that the mixing process involved in this highly stratified situation was unclear. The lack of information for the design engineers to predict the quantity of saline material which would be removed under normal flow conditions indicated the need for a fundamental investigation of the process. This programme of work commenced in 1993, and the initial findings are reported in this paper.

Related research

It has already been established that the entrainment of the salt water is a function of the Richardson number, Ri, of the flow (Ellison 1959). The Richardson number is a measure of the ratio of the gravity forces to the inertial forces in a shear flow having a vertical density gradient. It is widely used a measure of the stability of the flow with regards to vertical mixing. It generally takes one of two forms, the bulk Richardson number

$$Ri_b = g \frac{\Delta\rho H}{\rho V^2}$$

where $\Delta\rho$ is the density difference, H is the depth of fresh water and V is the average velocity, and the gradient Richardson number

$$Ri_g = -g / \rho \frac{\delta\rho / \delta z}{[\delta\rho / \delta z]^2}$$

where $\delta\rho/\delta z$ is the density gradient and $\delta v/\delta z$ is the velocity gradient. Turner (1973) and Christodolou (1985) further classified the type of mixing to be dependent on the magnitude of the Richardson number. A critical gradient Richardson number of 0.25 was found to be the limiting criteria between stable and unstable flow.

Experimental facility

To allow a wide test range, upto prototype conditions, a new facility was constructed within the Civil Engineering Department. This new facility consisted of a testing area 20m long, 0.75m wide and 0.75m deep a schematic of which is shown in Figure 1. The salt water was retained between two baffles which were 17.5 m apart. The salt water depth was kept constant at 0.25m whilst the fresh water depths were varied by means of an adjustable weir. The ability to produce conditions in which the saline water was either stationary or flowing, either with or against the prevailing river flow, was included thus allowing the simulation of tidal movements. The results

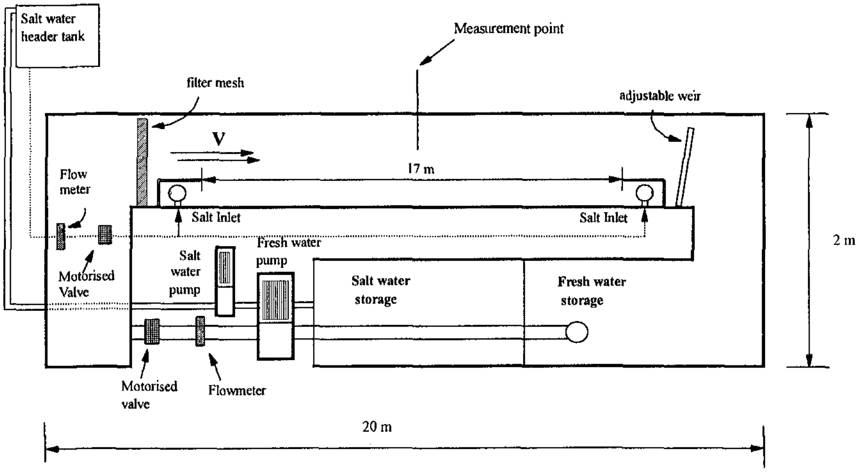


Figure 1 Experimental Facility

presented here represent the condition of a fully trapped saline wedge. Fresh water was mixed with dried salt and dye in the storage tanks and then pumped into the salt water impoundment to a depth of 0.25m. Fresh water was then filled slowly on top, over the course of 12 to 15 hours. Flow was initiated slowly in the upper layer by starting the fresh water pump. Once the flow had reached the required rate the water in the storage tanks was changed slowly by opening the waste valve and filling from the supply. This was necessary due to the contamination of the fresh water which occurred as a result of mixing. The degree of contamination was relatively small in most cases, but large enough to change the salinity of the fresh water over a substantial time period.

The scanning process was commenced after flow was initiated. Velocity and density profiles were obtained at the centre of the channel. Velocity measurements were obtained using LDA with a fibre optic attachment to limit the effeet of differing refractive idices. Density measurements were obtained using a conductivity probe with small measuring volume. The probe consisted of two wires 5 mm thick whieh were completely covered except for 2 rings, 2mm thick, near the bottom. Both probes were mounted on a linear actuator which was computer automated. The probes were placed in the salt water, usually about 20 to 30mm below the interface in order to obtain a reading of maximum salinity. An average was taken over a period of 30 seconds and the probes were then moved in a 5 mm step so that the vertical density profile could be obtained. Due to the temporal nature of the experimental investigation it was necessary to obtain as many profiles per hour as possible. The profile obtained was therefore not a full vertical traverse but was limited to 120mm around the interface. With time the interface moved downwards, as salt water was removed by entrainment from the impoundment, and it was necessary to incorporate movement of the base profile position into the scanning program.

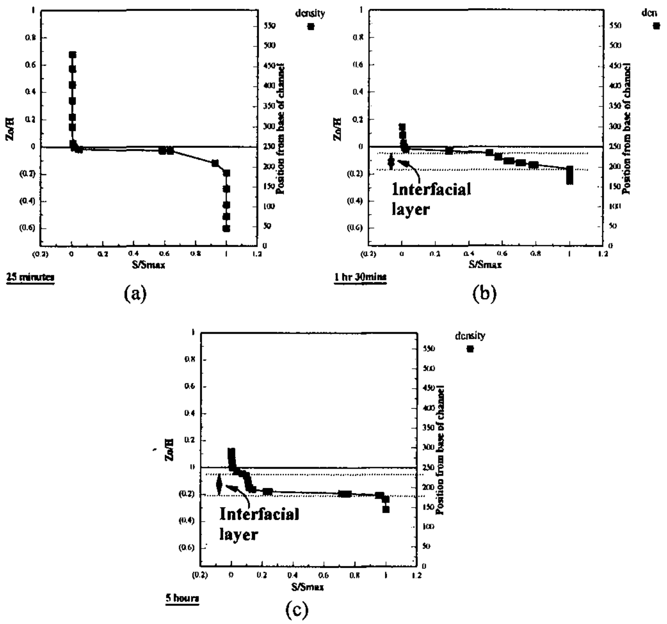


Figure 2 Density profiles (a) After 25 minutes (b) After 1 hour 30 minutes (c) After 5 hours

Development of Interfacial Layer.

The development of the mixing interfacial layer, as fresh water was allowed to flow across the stationary salt wedge, was studied with time. Figure 2 (a) shows the initial condition used in all tests. It clearly displays the fresh and salt water zones. Figures 2 (b) and 2 (c) are for the same situation, but with time having advanced to 1 hour 30 minutes and 5 hours respectively. The presence of a flow in the fresh water can be seen to have developed an interfacial layer, in that there is no longer a clear distinction between the fresh and salt water. It is from within this interfacial layer that the majority of entrainment of the saline liquid takes place.

This is clearly visible by the changing density gradient within the interface. The density within the interfacial layer was taken to be the average value within the density gradient of the layer. Figure 3 shows the interfacial layer in detail. It can be seen that the layer is defined by that position of the mixing region over which the variation of density occurred, this variation being taken as linear for purposes of analysis. The thickness of the interfacial layer was also obtained on this basis.

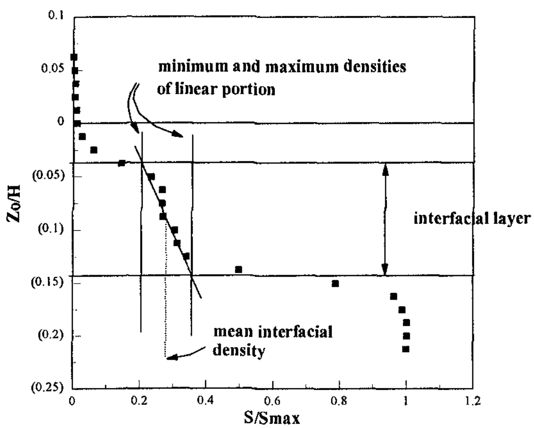


Figure 3 Definition of interfacial layer

It was found that the behaviour of this layer varied with certain combinations of flow, depth and density difference, and two mechanisms of erosion existed. In the first of these the wedge was eroded by sequential stripping of the interfacial layer, this process was labelled as oscillating due to the cyclic nature of the event. The second mechanism showed no such cyclic behaviour, with the density of the mixing layer decreasing to a steady state value. This mechanism was labelled as being non-oscillating. Significant differences in the temporal development and entrainment process was found for each mechanism.

Oscillating mechanism

Using the density profiles obtained from the experimental investigation, the layer position was plotted with time. Figure 4 represents a typical test which displayed the cyclic behaviour. On it can be seen the change, with time, in thickness of the interfacial layer and the density within that layer. The decrease in layer density corresponds with an increase in the layer thickness, this is as would be expected and closely mirrors the initial stage of the steady state condition. However, a critical point is reached where upon the density within the layer starts to increase again, with a corresponding decrease in the layer thickness. This corresponded to a period of rapid upper boundary movement when part of the layer was washed out. When the layer was at its thinnest there appeared to be an increase in the lower boundary movement,

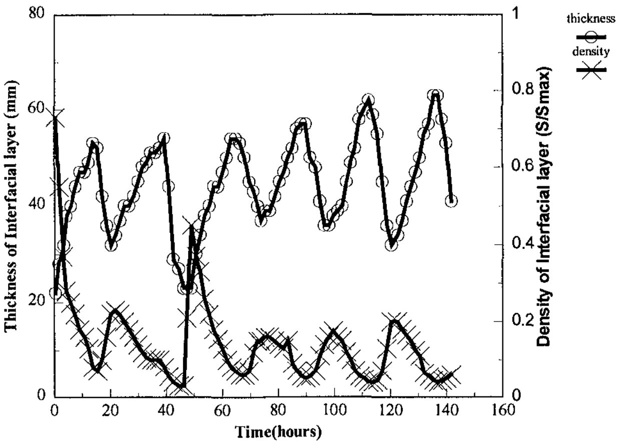
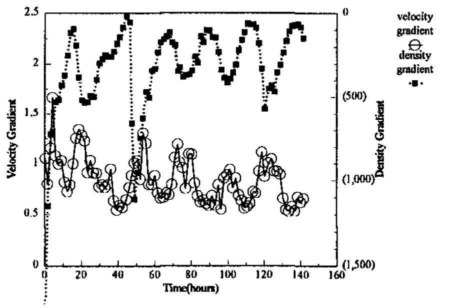


Figure 4 Relative interfacial layer density and thickness (oscillating mechanism)

as the free stream was now much closer to this boundary. This resulted in entrainment from the salt pool within the wedge. It would appear that for the oscillating process as the density of the layer decreases, the interfacial slope increases in order to resist the interfacial shear stresses. Figure 5 shows the variation of typical velocity and density gradients. These also show a definite cyclic behaviour with the maximum velocity gradients occurring when the layer was most dense.

If the change in the gradient Richardson number is examined, as shown on Figure 6, it can be seen that when the upper part of the layer was removed, the value of Ri dropped to approximately 0.25. As this represents the critical Richardson number it implies that the flow becomes unstable at these times, and this was confirmed by the presence of large amplitude breaking waves.



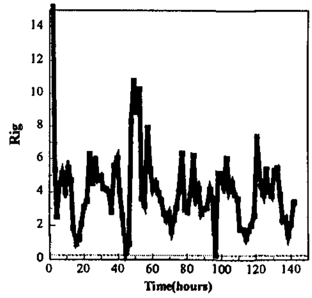


Figure 5 Interfacial velocity and density gradients (oscillating mechanism)

Figure 6 Variation of gradient Richardson number (oscillating mechanism)

Non Oscillating mechanism

Whenever no oscillation of the mixing layer charatceristics occurred the removal of the trapped saline solution progressed steadily with time. The time taken to achieve this varied with the magnitude of the circulation velocity within the mixing layer. Figure 7 shows the typical variation of the interfacial density and layer thickness for those tests which eroded at a steady rate. An initial high growth rate of the mixing layer occurred both in thickness and density, where upon almost constant conditions prevailed, and the saline pool was steadily depleted. Comparison with the equivalent figure for the oscillating test (figure 4) shows clearly the different mechanism of erosion in action. The velocity and density gradients also can be seen, in figure 8, to remain constant once the layer became established, as did the gradient Richardson number. Figure 9 gives an indication of typical variations in the Richardson number for non oscillating tests. The accepted threshold of instability in the flow occurs when the Richardson number fall below a value of 0.25.

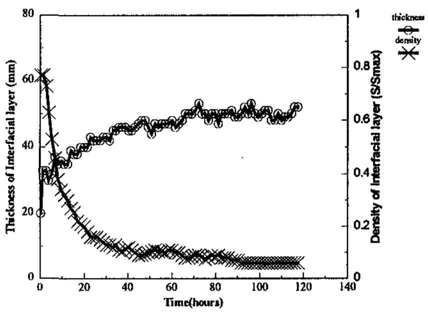


Figure 7 Relative interfacial density and thickness (non oscillating mechanism)

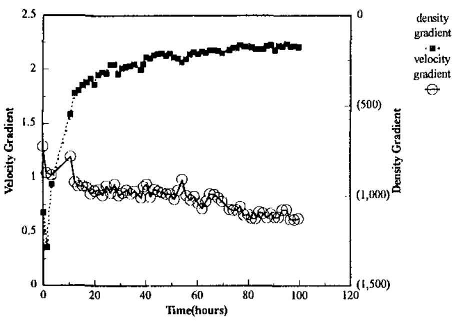


Figure 8 Interfacial velocity and density gradients (non oscillating)

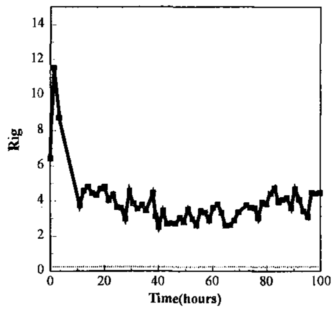


Figure 9 Variation of gradient Richardson number (non oscillating)

At no point during any of the tests which showed no oscillation did the Ri_g number approach this threshold. The key to the two mechanisms is therefore clearly a function of the flow instability.

Transport Rates

The changes in the density profiles obtained at different times during each test were used to determine the rate of erosion of the salt water impoundment. Transport across the upper boundary gave the overall rate of salt water removal during the test. This was calculated by approximating the profile, as can be seen in Figure 10, based on the position of the boundaries and the density of the layer. This allowed the volume of salt to be calculated very easily, with the differences between profiles at different times being taken as the as the volume of salt water transported. Any change in density of the interfacial layer, or drop in position of the upper boundary, was deemed to be due to transport across the boundary. Transport rates across the lower boundary were determined in a similar manner.

Based on a dimensional analysis, a dimensionless form of transport was used. This dimensionless transport. T, was defined as

$$T = \frac{t}{\Delta\rho V H}$$

where t is the average transport (kg/s), Δρ the initial density difference, V the initial average fresh water velocity and H the initial fresh water depth.

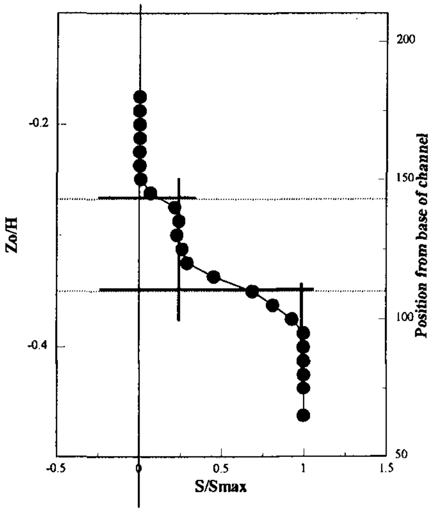


Figure 10 Stepped approximation for density profile

Figures 11 and 12 show the average transport rates obtained for the oscillating and non oscillating mechanisms respectively, plotted against the bulk Richardson number. It can be seen that in each case there exists a strong linear relationship between the rate T, and the Ri_b value, and that the rate obtained for each mechanism is similar, with the major difference occurring in the rates across the upper and lower boundaries.

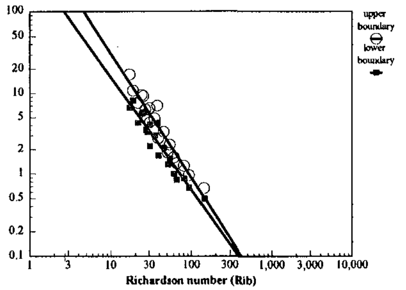


Figure 11 Dimensionless transport rates (oscillating mechanism)

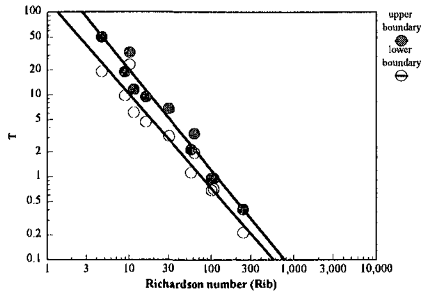


Figure 12 Dimensionless transport rates (non oscillating mechanism)

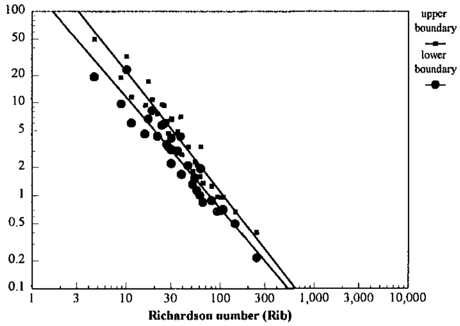


Figure 13 Dimensionless tranport rates for both mechanisms

Figure 13 is a combined plot for the transport rates obtained for both mechanisms of erosion. It can be seen that within each mechanism the transport rates were similar and could be best described by equations of the form

$$Tu = 447.2\ Ri_b^{\ -1.303}$$

for the transport across the upper boundary and

$$Tl = 184.2\ Ri_b^{\ -1.2}$$

for the transport across the lower boundary.

Conclusion

In all cases interfacial mixing resulted in the formation of an interfacial or mixed layer which was around 30 to 40 mm thick. Only those tests conducted with low values of Reynolds number(i.e. <2000) showed no mixing.

Two mechanisms of erosion have been observed. These were classified as oscillating and non-oscillating, depending on the behaviour of the layer in terms of its relative density and thickness. In some tests the density of the layer decreased rapidly, and then remained constant and these were classified as non-oscillating. In a number of cases the density within the layer decreased initially and then increased again after the upper part of the layer was removed. These tests were classified as oscillating as a cyclic behaviour was observed in the layer density.

The gradient Richardson number remained approximately constant during those tests which did not oscillate, indicating a stable flow. For those tests which showed the oscillating behaviour, the value of Rig was found to show a cyclic behaviour. When the layer was washed out, the value of Rig dropped towards 0.25, indicating unstable flow. Mixing occurred as a result of large amplitude breaking interfacial waves.

After the start of a test greater rates of transport were observed at the upper boundary as the layer formed. This resulted in a decrease in density until the layer washed out and a peak rate was observed at the upper boundary. Greater rates of transport were observed at the lower boundary when the layer was thinnest. This caused the density of the layer to increase with time.

Average transport rates were calculated during each test from the change in density profiles. Rates were averaged over the duration of the test and calculated for both boundaries. Dimensionless transport rates were found to be best related to the bulk Richardson number (Rib) with higher rates of transport for low values of Rib.

It is hope that the ability to estimate the removal rate of trapped salt water will aid the process of barrage design, and act as a tool for river management schemes by which the inducement of natural mixing can be accounted for.

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