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EXPERIMENTAL INVESTIGATION OF THE EXPULSION OF SEAWATER OVER ESTUARIAL BARRAGES USING BAFFLES

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Abstract: Many tidal barrages have recently been constructed in the United Kingdom in order to rehabilitate derelict urban land. The resulting permanent water body provides for many amenities such as water sports etc. In most cases, saltwater flows over these barrages during high tide creating a heavy salt layer under the fresh water. In certain conditions of slight mixing little reoxygenation of the lower layers takes place leading to low levels of dissolved oxygen and possible anoxia. One possible solution is to use a baffle just upstream of the barrage in order to retain freshwaters and confine stratification. This will force the saltwater tidal influx to flow down under the baffle and into the freshwater impoundment. At the end of the tidal period, river flow will push the saltwater under the baffle and over the barrage. This paper describes some of the experiments obtained using two experimental arrangements in order to illustrate some aspects of these phenomena.

1. INTRODUCTION AND SOME THEORETICAL CONSIDERATIONS

Many interesting phenomena are associated with the interaction of river and tidal flows and their effects on entrainment and mixing in marinas, harbours and other impounded bodies of water. The degree of mixing and entrainment depends greatly on the size and depth of the impoundments. In the case of small impoundments (Fig. 1), complete mixing takes place quickly and the effects of stratifications and differences in concentrations of various parts of the impoundment can be ignored (Wearing, 2000). Analytical solutions of the governing equations of the tidal model prism exist for simulating two different pollution regimes: (a) A flushing mechanism, where an initial, well-mixed pollutant diminishes in concentration due to the action of the tide; (b) The second mechanism is that of a continuous feed of pollutant entering the harbour, counteracting the flushing action of the tide. The above solutions were verified by Wearing (2000). Large, deep impoundments represent much more complicated flow situations. Starting from a position in the river at the tidal limit, when the whole water body will be made up of seawater of various degrees of salinity. A sudden increase in the freshwater river flow will result in a flow pattern similar to that generated by a two-dimensional buoyant surface jet (Fig. 2). The presence of a barrage and tidal flow will modify the flow patterns, as shown in Figure 3 (Dyrynda, Burrows and Ali, 2000).

2. THE SURFACE JET

River flow can be considered to be a two-dimensional turbulent shearing flow of a lighter fluid flowing on top of a heavier ambient fluid of a heavier density. The effect of stable stratification on the rate of entrainment will be influenced by temperature and density gradients. The turbulent characteristics of such a flow have been studied by many workers (Chu and Vanvari, 1976). It was found that the entrainment coefficient depends on the local Richardson number. Also, the entrainment characteristics of such a flow are generally influenced by the upstream and downstream conditions. A 'density jump' was also observed. Upstream of the jump the flow is jet-like and is characterised by turbulent mixing and entrainment similar to a neutral wall jet. This region is usually referred to as supercritical as it is only influenced by the upstream conditions only. Downstream of the jump the flow is distinguished by sharp interface with little entrainment. Mixing in the region of the density jump is very complicated. Reverse flow is usually observed near the interface where entrainment is resulting from the breaking of internal waves. Typical velocity and buoyancy profiles in the supercritical region are shown in Fig. 2.

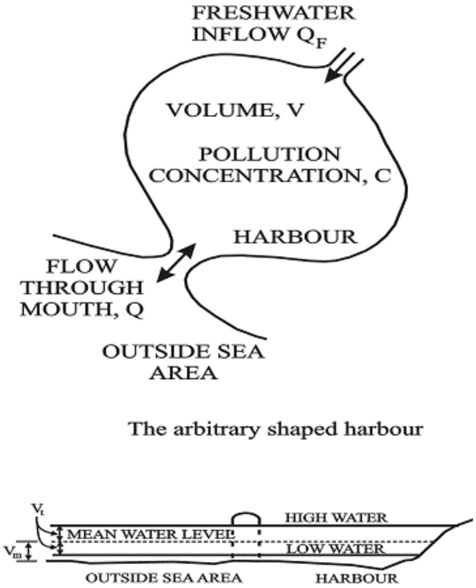

Fig. 1 Tidal regime in a harbour

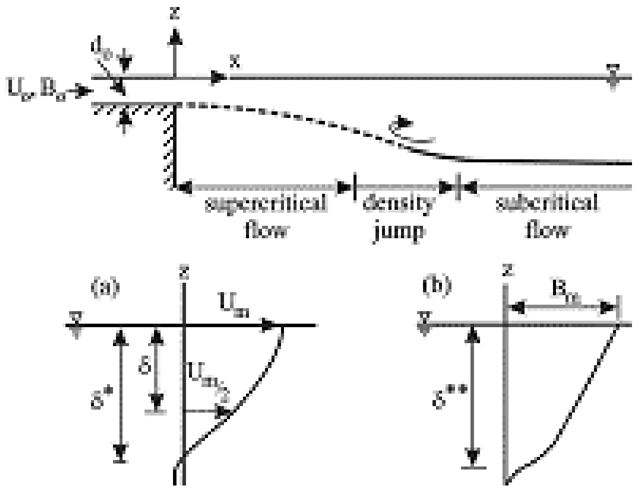

Fig. 2 Schematic diagram of typical flow situation: (a)velocity profiles; (b) buoyancy profile

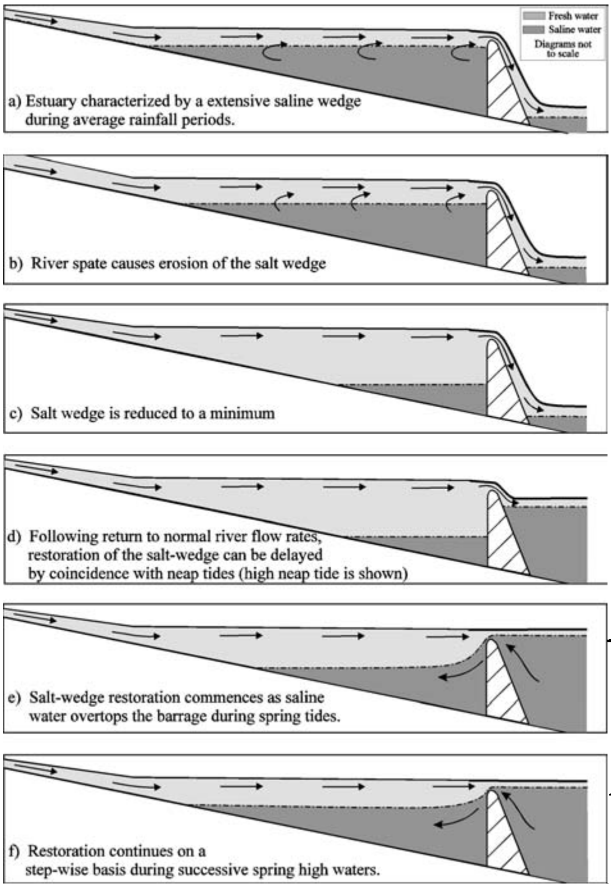

Fig. 3 Schematic of conditions in the impoundment (After Dyrynda, 1994)

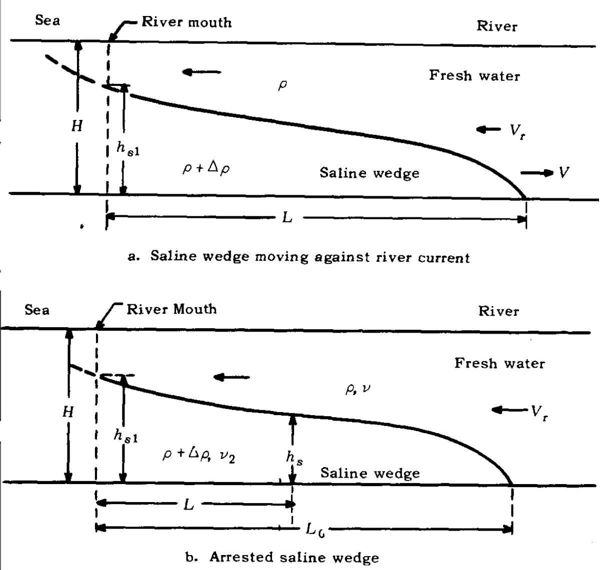

Fig. 4 Definition sketch for a saline wedge

3. SALINE WEDGES

The intrusion of salt in a river leading to a tideless sea is affected by the motion upstream of a definable and limited saline layer underlying the fresh water. This is called a saline wedge. Irrespective of the initiating circumstances, with river flow, water depth, and seawater salinity remaining constant, the advancing or retreating motion eventually ceases. The still form is called an 'Arrested salt wedge'. These phenomena are constantly observed in the lower reaches of rivers, particularly during seasons of reduced river discharges. Experience indicates that when fresh water moves over a stagnant pool of salt water or over an arrested saline wedge, mixing occurs when the velocity, U_c (Fig. 4). The salt is carried into the freshwater by the mechanism of breaking internal waves. Ippen (1966) gives the following expression for the amount of salt transported to the sea by freshwater $q_s = k^1(V_r N - U_c)s_o L_o$ where s_o = salinity of salt water; L_o = length of the salt wedge; k^1 = constant and N is a parameter dependent on the shape of the saltwedge.

4. SEAWATER DISCHARGE UNDER A BAFFLE

A baffle or a skimmer wall can be used to expel seawater from impoundments when stratification is present. Harleman and Elder (1965) give the following relationships for the maximum flow rate per unit width, q_c, and the incipient rate, q_d, (Fig. 5).

$$q_c = \sqrt{g\frac{\Delta\gamma}{\gamma}\left(\frac{2}{3}h_r\right)^3} \qquad (1)$$

and

$$q_d = 2.6 q_c \sqrt{\frac{\frac{h_r}{b}-1}{\left(\frac{h_r}{b}\right)^3}} \qquad (2)$$

where γ = specific weight of seawater, γ -$\Delta\gamma$ =specific weight of freshwater; g = acceleration due to gravity; b=gap opening and h_r=height of interface above the bed (Fig. 5). The variation of q_d with h_r for different values of b is given in Fig. 5). This figure shows that for a given value of h_r, q_d increases with b. Fig. 6 shows variation of q_d with b for given values of h_r. This figure shows that for a given value of h_r, there are unique values of q_d and b. For any lower value of q_d, there are two values of b for the same q_d.

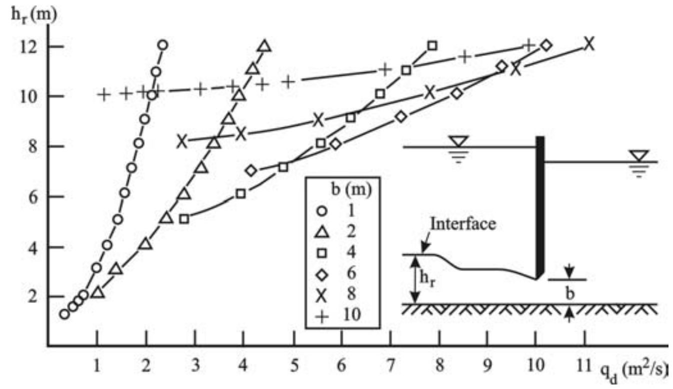

Fig. 5 Plot of h_r vrs q_d for given b values

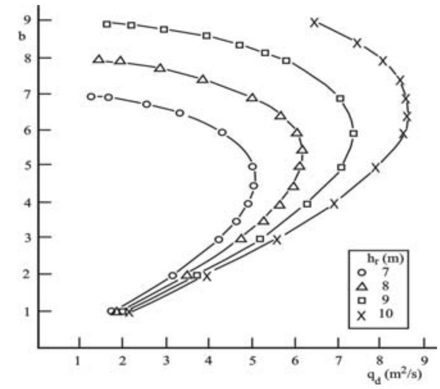

Fig. 6 Variation of q_d with b for given h_r values

5. EXPERIMENTAL ARRANGEMENTS AND MODELS

The experiments described in this paper were conducted in two different flumes. The first was 3.5m long, 0.1m wide and 0.35m high. A barrage or a barrier 0.25m high was positioned towards one end of the flume in order to produce as large an area as possible to represent the river impoundment. Figure 7 and 8 gives an overview of the flume. The bed slope of the flume was 0.004. Overflows were positioned at both ends of the flume to allow the expulsion of fresh and saltwater from the flume. In some of the experiments a baffle was located at a distance of 0.15m from the barrage (Fig. 7, 8). Baffle openings of 21mm and 42mm were used. The second flume was the Race Track Flume (TRF) which is shown in Figure 9. The flume consisted of two semi-circular bends of internal radius of 0.75m joined by two straight sections 4m in length. The flume was 0.3m wide and the maximum working depth was 0.6m. The working section of the flume was constructed of 12mm thick plate glass panels and the rest of the flume was made of 2mm thick galvanised steel. A toothed belt paddle was used at the water-surface to produce the flow. The paddle was positioned as far as possible away from the working section. The paddle was powered by an electric motor with a transformer given a continuously variable output for surface current speed control. The method of producing two-layered flow is similar to that described by Whyte (2003). Water-temperature and density were measured using a DMA35 oscillating-u-tube density meter manufactured by Paar Scientific Ltd. A Nixon Streamflow mini-propeller meter was used for measuring the velocity of the top layer. The Ultra Sonic Velocity profiler was used to obtain detailed velocity profiles (Whyte, 2003).

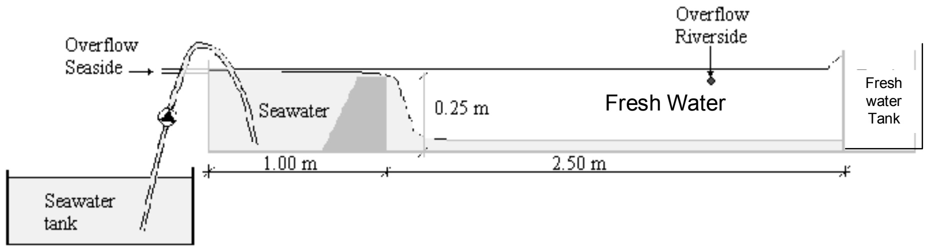

Fig. 7 The small barrage - flume

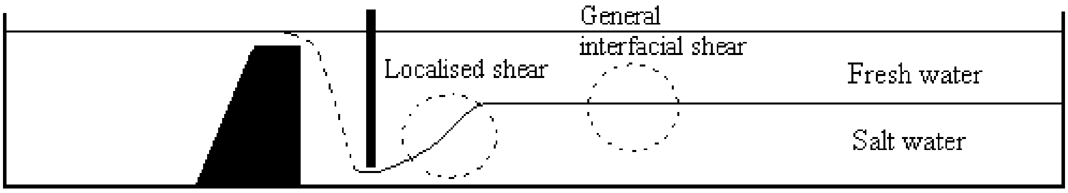

Fig. 8 Two possible types of entrainment

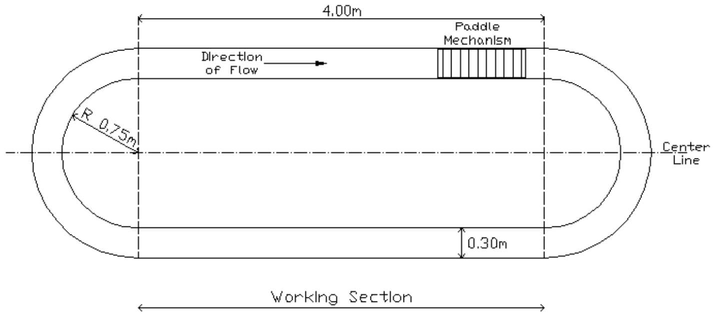

Fig. 9 Overview of the race track flume

6. EXPERIMENTS CONDUCTED IN THE SMALL FLUME

This model was a simplified model of the tidal estuary and barrage at Swansea, South Wales, UK (Rovers, 2000). Dynamic similarity of the densimetric Froude number resulted in freshwater river flow of 0.031 l/s and seawater flow of 0.062 l/s. Experiments were conducted for seawater densities of 1015, 1020 and 1025kg/m^3. Another series of experiments was conducted in which the flows were increased by a factor of 1.6. A typical time-scheme for these experiments was: (a) 0 minutes−start of experiment; (b) 0 minutes−

start of seawater flow over barrage; (c) 10 minutes − freshwater flow starts to enter flume; (d) 15 minutes − end of seawater flow; (e) 90 minutes − end of freshwater flow. Similar experiments were conducted using baffles with openings of 21 and 42mm. Velocity and density profiles were obtained at three sections and at 5 time intervals. Typical density and velocity profiles are given in Fig. 10 and 11. Four different types of experiments were conducted in the Race Track Flume in order to study different phenomena: (a) General two-layered flow produced by freshwater flow over a stationary saltwater layer; (b) Mixing caused by a saline layer overtopping a barrage; (c) Effect of positioning a baffle, down stream of a barrage, an entrainment; and (d) Entrainment caused by a heavy seawater jet flowing in the upstream direction.

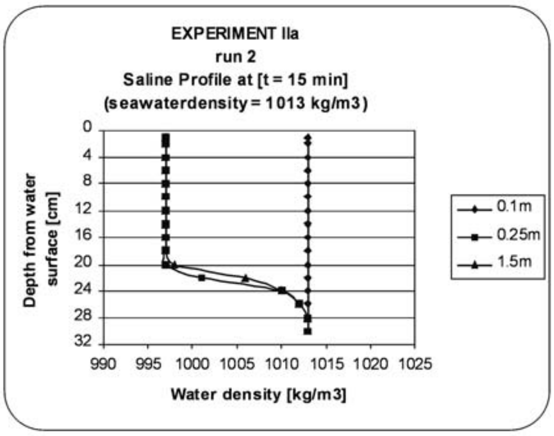

Fig. 10 Salinity profiles in impoundment in experiment Iia Run 2

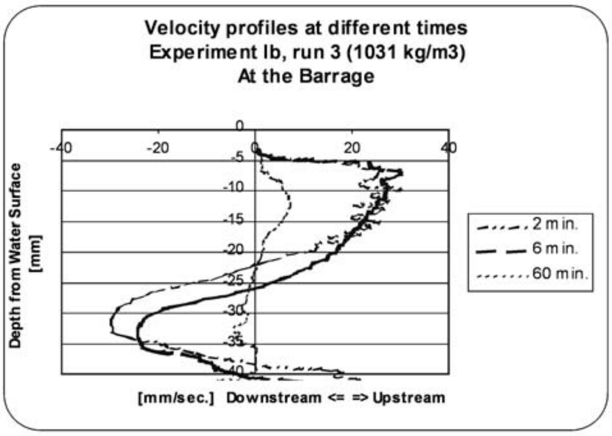

Fig. 11 Velocity profiles over the barrage In experiment Ib Run 3

THEORETICAL AND EXPERIMENTAL RESULTS

Extensive work was carried out at Liverpool but only a small part of these will be described herein.

7. THE SURFACE JET

For very small freshwater depth, h, and flow velocity, U, we will have a surface jet with supercritical flow. For example, for a water depth, h of 0.1m and velocity U of 2 m/s, the densimetric Froude number, F_i, will be 167 and the Richardson number, $\boldsymbol{R_i}$ will be 10×10^{-2}. A depth of 1 m and velocity of 0.2 m/s result in $F_i = 0.17$ and $R_i = 6$, giving $E = 3.1\times10^{-4}$, compared with $E = 0.18$ for a buoyant jet (E = entrainment coefficient) . For $h = 1$ m, $U = 1.2$ m/s, $F_i = 6$ and $\boldsymbol{R_i} = 0.17$ giving $E = 0.047$. These results show how the freshwater flow changes from a buoyant jet with large entrainment to interfacial mixing for $F_i < 1$ with much smaller values of E (Chu and Vanvari, 1976).

8. SEAWATERFLOW UPSTREAM OF BARRAGE

8.1 EXPERIMENTS USING THE SMALL HYDRAULIC MODEL

At the start of a typical run, the saltwater overshot the barrage as a jet and then dropped down past the barrage because of its negative buoyancy. At the bottom, the plunging saltwater resulted in some turbulence and a heavy plume was observed to travel upstream. Average velocities of the plume were calculated and found to be 26, 35 and 44 mm/s for saltwater densities of 1015, 1020 and 1025 kg/m^3 respectively. The above Richardson number $\boldsymbol{R_i}$ of 0.7 - 14 and of densimetric Froude number $\boldsymbol{F_i}$ of 0.29 and 0.1 ($R_i = g'h/u^2$, g' =

$g(\rho_1 - \rho_2)/\rho_2$ and $F_i = u/(g'h)^{1/2}$). Calculations using two-dimensional buoyant jet theory showed that dilution of the jet at the base of the barrage was small (1.2−1.7).

8.2 EXPERIMENTS USING THE RACE TRACK FLUME

Fig. 12 shows interface profiles downstream of the barrage taken at short time intervals. The densimetric Froude number for this experiment was 3.94. Here, we are dealing with a two-dimensional jet with negative buoyancy. The jet expands and mixes with the surrounding fluid and it transforms into a plume near the base of the barrage. After the first few seconds, dilution near the base is about 7 times that of the incoming flow and the half width is about 9.07 m. Abraham's (1955) trajectory results indicate that the jet will almost be vertical. The average velocity of the bottom plume was measured to be 0.021 m/s. This value is very close to that calculated from Harleman's expression for the velocity of an internal surge following the removal of dividing wall (0.024 m/s).

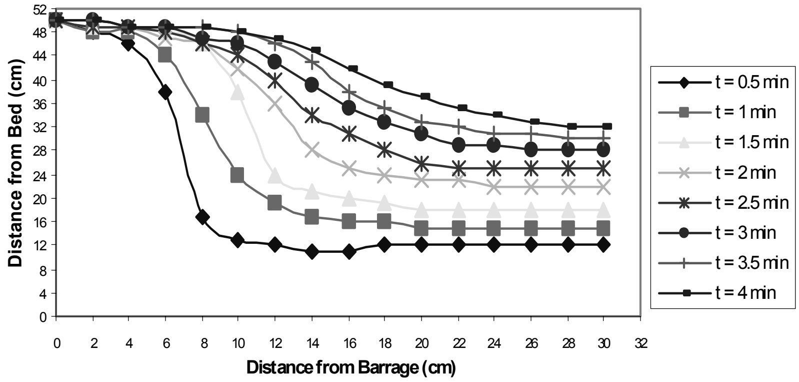

Fig. 12 Details of saltwater overtopping barrage

8.3 TWO-LAYERED SHEAR FLOW

The effects of two-layered shear flow were investigated using the Race Track Flume. Six experiments were conducted in the RTF without any barrages or baffles. Six different saline water densities were used together with three different paddle speeds. In most cases the general density and velocity distributions can be well-represented by Fig. 13. Assuming the velocity-distribution of the freshwater layer to be represented by a power law, the authors obtained an expression for the variation of interface level with time. Fig. 14 shows predicted interface levels for various values of the coefficient, c, in relationship, $E=c\boldsymbol{R}_{io}^{-1}$ where E = entrainment rate and $\boldsymbol{R}_{io}$ is the gradient Richardson number. Fig. 14 shows that entrainment is much bigger for large values of c.

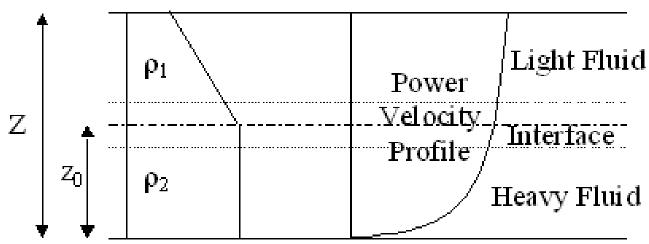

Fig. 13 Schematic of initial conditions considered in ali's power velocity profile analysis

9. CONCLUSIONS

Several interesting phenomena including entrainment by buoyant jets and plumes, saltwedges, interfacial mixing and baffle discharges were studied in this paper. Two hydraulic models and many measuring devices were used for this purpose. Useful results were obtained regarding flow types and behaviour. This work shows that large scale models with little or no vertical exaggeration must be used in order to accurately predict prototype flow patterns. Attempts must be made to apply some of the latest computer packages such as FLUENT to this kind of problem.

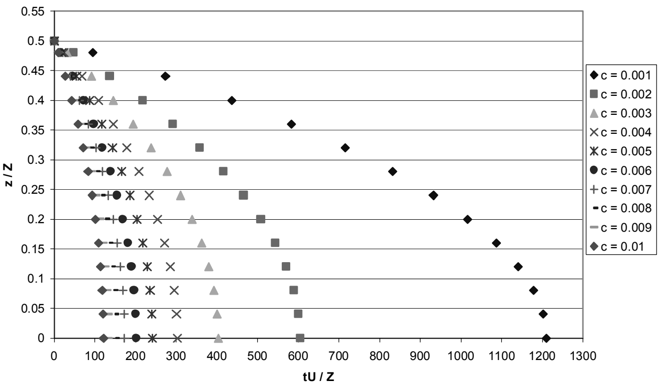

Fig. 14 Interface propagation rates using Ali's analysis for different values of c

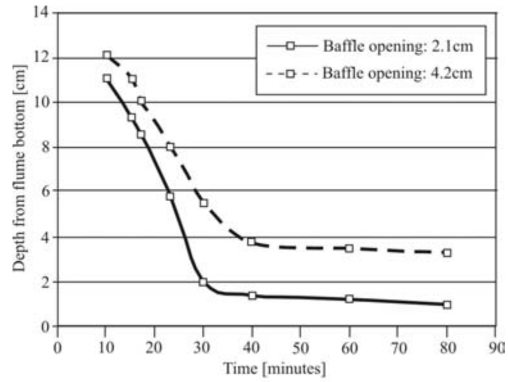

Fig. 15 Expulsion & entrainment during Experiments II and III

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REFERENCES

Abraham, G. (1965), "Horizontal Jets in Stagnant Fluid of Other Density", ASCE, Jour. of the Hyd. Div., Vol. 91, No. HY4, July, pp 139 - 150.

Ali, K. H M., Whyte, K., Bassiakus, S. and Burrows, R., "Experimental Study of Entrainment in Various Estuarial Barrage/Baffle Arrangements", XXX IAHR Congress, Thessaloniki, Greece, August 2003.

Ali, K. H. M. (2003), "Investigation of Some Aspects of Entrainment and Mixing in Bays and Harbours", Report, Civil Engineering Dept., University of Liverpool.

Baddour, R. E., (1987), "Hydraulics of Shallow and Stratified Mixing Channel", ASCE, Jour. of Hyd. Eng., Vol. 113, No. 5, May, pp 630 - 645.

Bassiakos, S., (2002), "Shear Flow Entrainment of Two Layered Fluids", M.Sc Thesis, University of Liverpool, Dept of Civil Engineering.

Burrows, R. and Ali, K. H. M., (2000), "Novel Boom/Skirt System for Improvement of Water Quality in Estuarial Impoundments Subject to saline Influx", 1st World Water Congress of the International Water Association (IWA), July, PP 485 - 492.

Chu, V. H. and Vanvari, M. R., (1976), "Experimental Study of /Turbulent Stratified Shearing Flow", ASCE, Vol. 102, No. HY6, June, pp 691 - 706.

Fisher, H. B., List, E. J., Koh, R. C. Y., Imberger, J. and Brooks, N. H. (1979), "Mixing in Inland and Coastal Waters", Academic Press.

Harleman, D. F. and Elder, R. A. (1965), "Withdrawal From Two-Layer Stratified Flow", ASCE, Jour. of the Hyd. Div., Vol. 84, No. HY2, April, pp 43 - 58.

Ippen, A. T. (1966), "Estuary and Coastline Hydrodynamics", McGraw-Hill Book Company, pp 546 - 565.

Rovers, C. (2000), "Expulsion of Salt Influx Over Estuarial Barrages Using the Baffle-concept", M.Sc Thesis, University of Liverpool, Dept of Civil Engineering.

Wearing, M. J., (2000), "Modelling of Pollution Transport in Small Tidal Harbours, Ph.D Thesis, University of Salford, U.K.

Whyte, K., (2003), "Numerical and Experimental Study of Mixing and Entrainment in Rivers", Ph.D Thesis, University of Liverpool, U.K.