Hydraulics Research
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VORTEX INHIBITORS

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ABSTRACT

Intakes in reservoirs often suffer from problems with vortices, particularly if they are sufficiently strong to produce a stable air core.

A programme of experimental research has been carried out to determine the effectiveness of a number of intake entrance configurations in reducing an incipient tendency to form vortices. Several configurations have shown promise in these tests, but sufficient work has not been done to enable an optimum geometry to be recommended.

Various of the published methods for predicting threshold conditions have been examined in the light of data from these experiments, and this has highlighted the need for further data.

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1 INTRODUCTION

Vortices have been the subject of innumerable investigations over many years but are still imperfectly understood. The majority of studies have been carried out in the laboratory, and have concentrated either on measuring properties of the vortex such as the surface profile and velocity distribution or on determining the overall conditions under which they form.

In the civil engineering field most problems with vortices occur either at pumping stations or at intakes in reservoirs, rivers or the sea. Vortices are normally undesirable because they can cause vibrations in intake structures and reduce the efficiency of pumps and turbines, the entrainment of air magnifies these problems and can produce surging in pipelines downstream of an intake. One of the major problems associated with the design of an intake is that of predicting whether vortices will occur under the planned operating conditions and, if they do, how best to prevent them. The most satisfactory ways of solving the problem are either to build a physical model or to use the results of previous investigations, which in most cases will have also been carried out in the laboratory. A satisfactory understanding of the scaling laws which apply to vortices is therefore needed if reliable predictions are to be obtained from model studies. Much research has been done on this topic, but so far it has not led to any widely-accepted method of scaling.

In the case of pumping stations progress has been made in dealing with the second question about how vortices should be prevented or inhibited. Guidance on suitable designs (see for example [1]) can now be given in terms of the necessary approach conditions, the geometry of the sump, the position of the suction pipe and the depth of submergence. Experience has also been obtained on how designs can be improved by using benching, baffle blocks and guide vanes. Less progress has been made on identifying satisfactory features for intakes in reservoirs. Designs are strongly influenced by site requirements so that they can seldom be applied elsewhere without modification and further testing. For this reason it is also difficult to compare results from different studies and establish which are the best types of vortex inhibitor.

The present report describes a research project on vortex inhibitors that has been carried out at Hydraulics Research (HR) with funding provided by the Department of the Environment. The primary aim of the study was systematically to compare different types of inhibitor for use with intake structures in reservoirs. Information from the tests should provide a better understanding of the mechanisms which cause vortices to occur in reservoirs. In order to carry out this research programme, HR has built two special test facilities; one consists of a large tank measuring 6m x 6m x 3.6m deep together with pumps, associated pipework and flow-measuring equipment; the other is similar in shape but smaller by a factor of 1:3.27. After considering previous work on vortices, this report describes the layout of the new facilities, their calibration and the results and conclusions from the test programme.

2 VORTEX THEORY

The concepts of circulation and vorticity form an integral part of any discussion of vortices. Although both these terms imply a rotational motion, their application is not confined solely to motion in a circular path, they can be applied equally well to motion that is essentially rectilinear, eg laminar flow between parallel plates.

Circulation is defined as the flow around the periphery of any closed circuit that lies within the fluid. It is equal to the integral of the velocity around the circuit.

$$\Gamma = \int v \, dl \qquad (1)$$

Γ = circulation

v = velocity component along element of circuit, of length dl

$\int$ = the line integral around the circuit

Even though fluid particles may not actually be circulating around the circuit, it is still possible for there to be circulation.

Vorticity is defined as the spin of an element of fluid around its own axis; it is a shift in the relative orientation of the axes of the element, during the course of its motion. Vorticity is a vector quantity and its component in any particular direction is equal to the net change in velocity gradient in the other two component directions. Thus the vorticity in the z-direction ζ_z, is equal to:

$$\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \qquad (2)$$

where

u = velocity in x direction

v = velocity in y direction

It can be shown that

$$\Gamma_{xy} = \iint \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) dx\, dy = \iint \zeta_z \, dx\, dy \qquad (3)$$

where Γ_{xy} is the circulation around a circuit in the x-y plane. In other words, the circulation in any circuit is equal to the total vorticity in the area bounded by the circuit. Similar equations can be derived for the circulation and vorticity in other component directions.

When the vorticity within a region of fluid is zero (and hence the circulation is also zero) the flow is defined as irrotational, and this condition will only apply to a non-viscous fluid. However, viscosity effects in real fluids are often concentrated close to the boundaries so that outside these regions the fluids behave as though they were effectively non-viscous. In such cases the flow patterns in real fluids can be predicted from the theory of irrotational flow, assuming an inviscid fluid.

The theoretical pattern for two-dimensional motion in a circular path, depends on the basic assumptions that are made. If it is assumed that the angular velocity of all the particles involved in the motion is constant, it follows that $\frac{v}{r}$ = constant (where v = velocity at radius r). Such flow will have a constant vorticity and will be rotational : this type of flow is described as a forced vortex.

If, on the other hand, it is assumed that the angular momentum of the rotating flow remains constant, i.e. vr = constant, the resulting flow pattern is described as a free vortex. The circulation in a free vortex depends on the choice of circuit. If the circuit does not include the origin, the circulation (and hence the vorticity) is zero. This can be demonstrated most simply by calculating the circulation around a circuit bounded by two concentric arcs and two radial lines. The flow outside the centre of the vortex is thus irrotational. If the origin is included within the circuit, the circulation has a finite value. For a complete circumferential circuit

$$\Gamma = 2 \pi r v \qquad (4)$$

The free vortex is thus a special case of irrotational flow. It has zero vorticity everywhere, apart from at the origin; the circulation around any circular path enclosing the origin is constant and is equal to the circulation corresponding to the concentrated the vorticity at the centre of the vortex.

Free vortex theory also leads to an unrealistic velocity distribution close to the centre, i.e. $v = \infty$ at $r = 0$. In practice, a real vortex exhibits characteristics of both the free and the forced variety : the central core behaves as a forced vortex, whilst the region outside the core conforms to a free vortex, with zero vorticity and with a circulation equal to that of the central core. Such a vortex is described as a combined or Rankine vortex.

There are many views on the cause of vortices. The one most commonly held, is that the vortex is produced by vorticity generated at a shear layer, at either an external solid/liquid boundary or an internal liquid/liquid boundary. Presumably the vortex is the mechanism by which the vorticity is transported out of the system in which it has been generated. However no explanation appears to have been advanced to explain why, if a vortex has formed, the vorticity has to concentrate and organise itself in such a fashion in order to be removed; why it cannot be transported out of the fluid in a more random fashion in a similar way to turbulence.

To date, the major part of the fundamental research on vortices has concentrated on studying the stable form with a well-defined air core that has been generated in equipment specifically designed to generate vortices. Little or no work has been done on identifying the processes whereby vortices are produced in circumstances that do not, on the face of it, have any incipient vortex-generating tendency, e.g. at the outlet of a tank in which the approach velocities are low and uniformly distributed over the flow cross-section.

3 SURVEY OF PREVIOUS RESEARCH

Useful summaries of earlier work on vortices are given by Chang who deals with drain vortices in cylindrical tanks [2] and vortices in rectangular pump sumps [3]. The purpose of the present section is to consider those studies that are particularly relevant to vortices at reservoir intakes, and uses references contained in a literature survey carried out by Wooldridge [4].

Results of vortex studies are often presented in non-dimensional form, but previous investigators have grouped the parameters in a variety of ways. The following is a brief summary of some of these groupings.

1. <u>Geometric parameters</u> The dimensions of the tank and the position of the intake may be related to the size of the intake (diameter D if circular), the depth of water H in the tank, or the submergence S of the centre of area of the intake.

2. <u>Reynolds Number</u> (ratio of inertial to viscous forces)

$$R_e = \frac{Q}{L\nu} \quad \text{or} \quad \frac{VL}{\nu} \tag{5}$$

where Q is the flow entering the intake, V the average velocity at the intake and L a dimension of the intake (eg the diameter D). Alternatives are

$$R_r = \frac{Q}{S\nu} \quad \text{or} \quad \frac{VS}{\nu} \tag{6}$$

which are termed radial Reynolds numbers by Anwar [5].

3. <u>Froude Number</u> (ratio of inertial to gravitational forces)

$$F = \frac{Q}{(gL^5)^{\frac{1}{2}}} \quad \text{or} \quad \frac{V}{(gL)^{\frac{1}{2}}} \tag{7}$$

An alternative type of Froude number is given by what is sometimes termed the coefficient of discharge

$$C = \frac{Q}{A(2gS)^{\frac{1}{2}}} \tag{8}$$

where A is the effective area of the intake

4. <u>Weber Number</u> (ratio of inertial to surface tension forces)

$$W = V\left(\frac{\rho L}{\sigma}\right)^{\frac{1}{2}} \quad \text{or} \quad V\left(\frac{\rho S}{\sigma}\right)^{\frac{1}{2}} \tag{9}$$

where σ is the surface tension, and ρ the density of the liquid.

5. <u>Kolf Number</u> (ratio of centrifugal to inertial forces)

$$K = \frac{\Gamma}{VL} \;, \quad \frac{\Gamma L}{Q} \quad \text{or} \quad \frac{\Gamma}{L(2gS)^{\frac{1}{2}}} \qquad (10)$$

where Γ is the circulation defined by Equation (1).

Some significant features of drain vortices which have been observed experimentally (see Daggett and Keulegan [6]) are:

1. the circulation Γ around a vortex does not vary with radial distance except within a central core whose diameter is approximately that of the outlet;

2. the radial velocity near the core is very small except close to the floor of the tank where the flow is concentrated;

3. the tangential velocity is almost independent of the depth;

4. both upward and downward vertical velocities occur within the core.

These findings show that viscous effects are confined to a core of relatively small diameter and that outside this region the flow is effectively irrotational; the core therefore represents a type of boundary layer, outside which viscosity is not significant. The results also show that the flow in a vortex is three-dimensional and cannot be described satisfactorily by simple two-dimensional models.

Many studies are concerned with identifying the critical flow conditions (submergence S_c or discharge Q_c) at which a vortex produces an air core that is just able to reach the intake. As described in Section 6, other stages in the development of a vortex may be used to define limiting flow conditions. A quantity such as S_c/L is normally assumed to be a dependent parameter, but it is less easy to categorise some of the dimensionless numbers described above. If the circulation Γ is forced by jets or vanes, the Kolf number K is an independent parameter; in a reservoir Γ is determined by the geometry and the fluid properties so that K is a dependent parameter. The quantity C in equation (8) only becomes a true discharge coefficient when applied to an orifice that discharges directly to atmosphere; C is then a dependent variable since Q and S are directly related. However if there is a pipeline or pump downstream of the intake, Q and S can usually be varied independently : C then loses its significance as a discharge coefficient and only represents an alternative and arbitrary type of Froude number.

Studies on vortices at horizontal and vertically-inverted intakes were carried out by Amphlett [7] and Anwar [8]. The experiments were performed in a flume 0.92m wide using pipes with diameters of D = 50.8mm, 76.2mm and 101.6mm. The horizontal pipes were mounted with their axes normal to the direction of the approaching flow, and vanes were used in order to strengthen and stabilise the vortices. Amphlett [7] presents results for the 76.2mm diameter horizontal pipe in the form

$$\frac{\Gamma D}{2\pi Q} = \text{fn}\left(\frac{Q}{\sqrt{S}}, C, \frac{S}{D}, \frac{(H-S)}{D}\right) \qquad (11)$$

The last factor on the right-hand side refers to the height of the intake above the floor of the flume, but was found not to be significant. The experimentally-determined curves of $\Gamma D/(2\pi Q)$ versus $Q/\sqrt{S_c}$ and S_c/D for the condition of critical submergence are shown in Figure 1; the curves separate the upper region in which air-entraining vortices occur, from the lower region in which they do not. Anwar [8] includes additional data for a 50.8 mm horizontal pipe and plots the results in the form

$$\frac{\Gamma r_o}{2\pi Q} = fn\left(\frac{Q}{\sqrt{S}}, C, \frac{S}{D}, W\right) \tag{12}$$

Here the Kolf number is defined in terms of the radius of the shadow which the vortex casts, by means of an optical system, on the floor of the flume. This radius was found to be related to the strength of the circulation by the formula

$$\Gamma = 0.86 \left(\frac{g}{H}\right)^{\frac{1}{2}} r_o^{\,2} \tag{13}$$

Fig 2 shows the experimental curve of $\Gamma r_o/(2\pi Q)$ versus $Q/\sqrt{S_c}$ for the condition of critical submergence; this method of presentation appears to remove the dependence on S_c/D. Both Figs 1 and 2 suggest that for a given flow the circulation strength needed to produce an air-entraining vortex tends towards a constant value as the radial Reynolds number R_r becomes large. Amphlett [7] and Anwar [8] also give plots which show how the Kolf number varies with the Froude number C and the Weber number W. However the tests were not carried out in such a way as to isolate the individual effects of the parameters R_r, C and W. It therefore seems probable that the curves in Figs 1 and 2 implicity include effects due to variations in C and W.

Daggett & Keulegan [6] studied drain vortices in circular tanks using eight different sizes of orifice and six fluids with various values of viscosity and surface tension. Flows were supplied circumferentially to the tanks and given swirl by means of adjustable vanes. Over the range of conditions tested, surface tension was not found to have a significant effect. Since the orifices discharged freely to atmosphere, the discharge coefficient C in equation (8) is a dependent parameter; properties of the flow are therefore determined by the non-dimensional Kolf and Reynolds numbers. Analysis of data for the condition of critical submergence gave

$$\frac{S_c}{D} = 17.5 \times 10^{-3} \left(\frac{\Gamma D}{Q}\right) \left(\frac{Q}{D\nu}\right), \text{for } \left(\frac{Q}{D\nu}\right) < 2.5 \times 10^4 \quad (14)$$

$$\frac{S_c}{D} = 37.5 \left(\frac{\Gamma D}{Q}\right), \text{ for } \left(\frac{Q}{D\nu}\right) \geqslant 2.5 \times 10^4 \quad (15)$$

Here S_c is measured from the plane of the orifice and so is slightly greater than the depth of fluid H in the tank. Γ is termed the initial circulation of the incoming flow and is calculated directly from the depth H and the angle of the vanes. Equation (14) shows that the critical submergence depends on both the Kolf number $\Gamma D/Q$ and the Reynolds number QD/ν when the latter is less than 2.5×10^4. Above this figure, S_c is only affected by the Kolf number and is independent of the kinematic viscosity of the fluid. The application of these results to other types of intake may be limited by the fact that the orifices imposed a particular relationship between discharge and head; in other situations where discharge can be varied independently of head it is necessary to take the effect of the Froude number into account. Also it is not clear from the description of the experiments whether the strength of the vortex inside the tank was equal to the initial circulation calculated from the angle of the vanes.

Jain, Raju & Garde [9] used a similar type of experimental arrangement to that of Daggett & Keulegan [6], but replaced the orifice by a vertical intake connected to a pump so that discharge could be varied independently of head. Tests were carried out in two circular tanks using intake pipes of six different diameters; the viscosity and surface tension of the water were varied by adding cepol and iso-amyl alcohol. The independent variables were grouped in such a way that tests could be carried out by varying only one non-dimensional parameter at a time. Thus the viscosity was grouped with the pipe diameter and the gravitational acceleration to give the parameter

$$N = \frac{g^{\frac{1}{2}} D^{3/2}}{\nu} \qquad (16)$$

This quantity is equal to the Reynolds number VD/ν divided by the Froude number $V/\sqrt{(gD)}$ and thus represents the ratio of viscous and gravity forces.

There must be some doubt over the use of the pipe diameter as the length dimension in both the Reynolds and Froude numbers. Is the Reynolds number of the flow in the pipe a true reflection of the influence of viscous forces on the formation of a vortex at the entrance to the pipe? Does the Froude number have any significance when applied to a pipe flowing full, in which free surface effects are absent? Such questions are relevant when these two dimensionless numbers are used to determine the limiting size of pipe for which viscous effects on a vortex are significant.

The Kolf number was defined as

$$K = \frac{\Gamma S}{Q} \tag{17}$$

where the value of Γ was calculated from the initial circulation produced by angled vanes around the periphery of the tank. This definition was used so that K would not vary with changes in water level or discharge but would only depend upon the geometry of the vanes. Analysis by Jain [10] of data for the critical submergence gave

$$\frac{S_c}{D} = \frac{5.6}{A_n} \left(\frac{\Gamma S_c}{Q}\right)^{0.42} \left(\frac{V^2}{gD}\right)^{0.25} \tag{18}$$

where A_n is a factor which takes into account the effect of viscosity:

$$A_n = 1 \text{ for } N > 5.5 \times 10^4 \tag{19a}$$

$$A_n = 29.5\, N^{-0.31} \text{ for } N < 5.5 \times 10^4 \tag{19b}$$

Surface tension was not found to influence the value of S_c provided

$$\frac{\rho v^2 D}{\sigma} > 120 \tag{20}$$

Equations (16) and (19) suggest that a model of a vertical intake using water at 15°C ($\nu = 1.14 \times 10^{-6}\ m^2 s^{-1}$) will only be subject to viscous scale effects if the diameter of the intake is less than 74mm. At first sight this criterion seems suspect because it does not appear to take flow rate into account. However, implicitly, this factor is allowed for, because the limit only applies to tests at the critical submergence. Thus it can be shown from Equations (16), (18) and (19a) that viscosity ceases to have an effect if the radial Reynolds number

$$\left(\frac{Q}{\sqrt{g}\,S_c}\right) > 1380 \left(\frac{\Gamma D}{Q}\right)^{-0.84} \left(\frac{S_c}{D}\right)^{0.16} \qquad (21)$$

Most, if not all, of the experimental data have been presented in the form of dimensionless groups, obtained by means of a dimensional analysis of the pertinent variables. An alternative, more analytic approach, has been adopted by Sanmuganathan [11]. He argues that the generation of an air-core vortex is the result of the interaction between a vortex creating a local depression in the surface, and the local low pressure region around the intake caused by the local acceleration there. The air-core becomes continuous to the intake when the circulation is sufficiently great to produce a surface depression that links up with the low pressure region around the intake produced by the discharge out of the system. Thus it would presumably be possible to produce a vortex by a combination of large circulation and moderate discharge or moderate circulation and large discharge.

One of the merits of the Sanmuganathan model is that it does put forward a possible mechanism for the formation of a continuous air core. The model leads to two dimensionless groupings of the pertinent variables, that also have the merit that they separate the discharge and the circulation. They are:

$$\alpha = \left[\frac{Q^2}{8\pi^2 g\, S^5}\right]^{1/5}; \quad \beta = \frac{\Gamma^2}{gSt^2}$$

where t is the radius of the forced vortex at the core of the free vortex. An equation relating t to the pipe diameter and the submergence, has been put forward.

A variety of vortex inhibitors has been used for reservoir intakes, but they can be classified by the positions in which they are placed

1. at the surface

2. between the surface and the intake

3. at the intake

Floating rafts (e.g. at the Kariba dam [12]) can be used to prevent air entrainment, but the tendency of vortices to migrate around intakes may render them ineffective. Inhibitors positioned between the surface and the intake usually consist of walls or screens which reduce the strength of the vortex by viscous dissipation. In the Bear Swamp [13] type of intake the vertical shaft is surrounded on three sides by vertical walls with the fourth side open to flow approaching along a narrow tapered channel. Alternatively the vortex motion may be damped by means of bars or perforated screens placed above or in front of the intakes; examples include the baffles used for Victoria Dam [14] and the Orange River Project [15]. The third category consists of flow straighteners, which are positioned at an intake in order to eliminate swirl; an example is provided by the vanes and vortex cap which were tested for the Prattsville pumped storage scheme [16]. A fourth method of preventing vortices is to alter the shape of the structure so that the region in which the vortices tend to form is no longer occupied by water; this can be effective but may be expensive.

A comparison by Hecker [17] of the model and prototype behaviour of various intakes led to the following conclusions and recommendations:

1. models operated according to the Froudian scaling law appear to predict accurately the onset of swirl at an intake:

2. viscous scale effects may become significant when modelling air-entraining vortices;

3. a limit for the satisfactory operation of an intake can be defined as the point at which a dye core forms between the surface and the inlet,

4. models of vortex inhibitors may overestimate the viscous damping that they would produce in the prototype.

4 LARGE EXPERIMENTAL TANK

A large tank, 6m square in plan and 3.6m deep was constructed; it was kept free of all internal bracing, in order to avoid generating any disturbances in the flow. The tank is supported on concrete piers approximately 0.8m high, and the space beneath the tank was enclosed in order to form a sump.

Water is supplied to the tank by two pumps with nominal capacities of 0.14 and $0.07m^3/s$: they can be operated singly or in tandem. Each pump feeds into a common 225mm pipe, which is connected with the inlet manifold (225mm diameter with 50mm dia holes, at 150mm centres, in the crown) running inside the tank, along the length of one of the walls. Hairlok screens have been installed in the tank, downstream from the inlet manifold, to still the incoming flow and distribute it uniformly over the cross-section.

The discharges from the pumps are measured by means of British Standard orifices installed in the discharge lines. The general layout of the test facility is detailed in Figure 3 and in Plates 1 and 2.

The outlet from the tank is by means of a 225mm pipe, located low down in the tank wall immediately opposite to the inlet manifold.

4.1 Pumping system

The water supply system was designed so that the flow could be generated either by gravity or by pumping. When the flow is gravity-produced, the tank outlet discharges directly to the sump, from which it is then drawn by the pumps and re-circulated through the tank. When the flow is being pumped, the outlet to the sump is closed off and the system operates as a closed loop. A short length of perspex pipe was installed in the outlet pipe, just downstream from the tank, to permit observations of the outflow and determine whether air was being drawn into the system.

4.2 Access to the tank

A working platform was provided along two sides of the tank, at the top of the walls. In order to gain access to the interior of the tank, particularly when tests are being carried out at low water levels, a movable working platform was constructed: this is mounted on rails, which allow the platform to be moved to any part of the tank. The height of the platform above the floor of the tank can also be readily adjusted, thus allowing it to be positioned close to the water surface, irrespective of the depth of water in the tank.

4.3 Water level measurements

For depths of water of 1.2m or less, the level can be measured by means of a micrometer point gauge mounted over a stilling well, outside the tank. In water depths greater than 1.2m, the level is measured by means of a gauge board, graduated in millimetres, mounted on the tank wall opposite to the inlet manifold.

4.4 Discharge measurements

Orifice meters were installed in each of the pump delivery lines. The orifice plates were manufactured according to BS 1042 : Part 1 and had diameters of 165mm in the 203mm pipe and 125mm in the 178mm pipe; pressure tappings were of the D and D/2 type in the 178mm pipe and of the flange type in the 203mm pipe.

5 VELOCITY DISTRIBUTION IN TANK

Initially, flow conditions in the tank were not completely satisfactory, with slow moving vortices forming on both sides. The velocity distribution across the tank was measured using an electro-magnetic flow meter and this showed that although the general pattern was satisfactory, there were some local areas of high velocity and of reverse flow. At this stage, only one hairlok screen had been installed, immediately downstream from the inlet manifold pipe. Clearly this was insufficient and an additional screen, similar to that already installed, was fitted 300mm downstream from the first. This produced an immediate improvement and flow conditions were acceptable.

6 EXPERIMENTAL PROCEDURE

The primary aim of the study was to compare the effectiveness of various types of vortex inhibitor. The procedure adopted was to carry out tests on each inhibitor at a series of fixed water levels, determining the limiting discharges at which selected categories of vortex action became apparent. This approach was less time-consuming than the alternative of keeping the discharge constant and systematically varying the water level.

Although a strong vortex with an air core is readily identifiable, there are various intermediate stages of vortex formation that are also important. For ease of classifying the different vortices that were produced, a scale of 1 to 6 was used in the assessment, where 1 represents the onset of a slight surface depression and 6 represents a stable vortex with a well-defined air core. Details of the classification are given in Figure 4.

The vortex categories that were used as bench-marks in the tests on the inhibitors were:

1. a small dimple forming on the water surface

2. floating material (small polystyrene pellets) drawn down into the outlet

3. well-defined air core extending from the water surface to the outlet

In practice, it is not possible to define precisely when these different stages first make an appearance. The vortices are slow to build up, they tend to be intermittent and can vary in strength from day to day, for no apparent reason. Repeatability is not always easy to achieve.

In order to have a base condition against which the performance of an inhibitor could be judged, tests were carried out initially with a vortex-prone intake. Subsequent tests have been carried out on the same basic, but modified intake.

7 BASE TESTS

(a) Flush intake

In many previous studies vortices have been produced by introducing the flow into the experimental facility with both radial and tangential velocity components. For the tests on the vortex inhibitors, the aim was to allow the intake configuration itself, to generate any vortex action.

For this reason the basic geometry was kept as simple as possible, ie the intake was located on the tank centreline, the flow was introduced into the tank as uniformly as possible and parallel with the intake centreline.

Initially the intake was installed with its entrance face flush with the wall of the tank, and with its invert 76mm off the tank floor.

The first tests were carried out with the maximum discharge that could be produced viz $0.205m^3/s$, and despite repeating the experiments at levels ranging from 0.8 to 2.9m, it was impossible to produce any significant vortex action: the most serious disturbance in the flow was a slight surface depression, which made an appearance only intermittently.

In an attempt artificially to encourage some vortex action, asymmetry of the flow approaching the outlet was produced by blocking off half the width of the screens, over the full depth of the tank. Although this did produce a more frequent appearance of the slight surface depressions, severe vortex action was still absent.

Previous experience suggested that an intake that permitted flow to approach it from all directions, instead of solely from upstream, might be more likely to encourage vortex formation. Accordingly, the intake was projected into the tank proper: this was achieved by inserting a 200mm diameter pipe into the existing intake, so that the entrance was now located 1.63m out from the wall of the tank. The partially blocked-off screens were retained.

Tests, similar to those on the flush intake, were then carried out. This time there was no difficulty in producing vortices, which in some cases had stable and well-defined air cores extending from the water surface to the intake.

(b) Projecting intake

The performance of the projecting intake was studied in detail. The outflow discharge was maintained at $0.19m^3/s$ throughout the tests and the water level was progressively lowered in steps of 130mm, for water depths ranging from 3.45 to 0.45m. Each test lasted several hours, in order to allow any incipient flow characteristics to make themselves evident. At each water level, the degree of vortex activity was judged on the scale of 1 to 6, and the results are shown in Fig 5: this shows quite clearly that there was strong vortex activity for water depths less than 2.5m. Plate 3 shows a vortex with a well-defined air core.

In addition to the assessment of vortex activity measurements of the velocity distributions upstream from the intake, were made for a discharge of $0.19 m^3/s$ and a water depth of 1.8m.

Several interesting features, which are relevant to the theories on vortex formation, emerged from these initial tests.

Vortex generation is commonly attributed to vorticity produced by shear at a solid boundary. The experiments with the flush intake showed that well-defined vortices could not be produced, whereas they were readily produced with a projecting intake. For a given discharge, the shear at the tank boundaries would have been the same for the two intakes. Hence boundary shear alone is not sufficient to generate the vortex: the vorticity must be produced by the intake itself or by the shear at an internal fluid/fluid boundary that results from the flow pattern created by the intake. In order to throw some additional light on this aspect, the data from one of the tests in which an air core formed was used to assess the vorticity generated at the tank boundary and that contained within the core of the vortex. This showed that the vorticity flux in the core was 2 or 3 orders of magnitude greater than the vorticity flux generated at the boundary. Although this in itself is not conclusive - it may be necessary to have a large vorticity flux in the vortex core in order to transport a much smaller vorticity flux out of the system - nevertheless it suggests that boundary shear alone might not be sufficient.

Another interesting feature was the variation in the vortex activity as the depth of water in the tank was varied. It is commonly held that vortex activity is most pronounced when the water depth is small, and that it tends to decrease as the water depth increases.

The observations made during the projecting intake tests did not support this view. Admittedly there was intense vortex activity (scale 6) at low water depths, which decreased (scale 4) for greater water depths. However as the depth of water in the tank was further increased, the vortex activity did not tail off but increased again to scale 6 at quite large water depths. This pattern of behaviour was consistent with that which had been observed at HR during a model study of a submerged vertical intake [15].

8 TEST PROCEDURE

The basic procedure when testing the various intake modifications, was as follows. The characteristics of each intake were investigated at three different water levels viz 1.2, 1.8, and 2.48m, the discharge being progressively increased until the selected flow features made their appearance in turn. Time-lapse photographs of surface floats were taken from above, from which surface velocities and hence the circulations (= $2\pi rV$) could be calculated.

The effectiveness of a particular intake modification was judged on the discharge at which the selected flow feature became evident, with the greatest weight attached to the onset of the vortex with an air core.

9 TYPES OF INHIBITOR

Reference has already been made to the concentration of research effort on the well-established vortex rather than on the mechanism whereby the vortex is generated. This has meant that the geometries of the various types of inhibitor that have been tested in this series of experiments, have been based on a variety of hypotheses about the vortex-producing mechanism.

A complete list of the intake modifications tested is:

1. Headwall, 0.61m high

2. Headwall, 1.22m high

3. Headwall, 1.83m high

4. Headwall, 2.44m high

5. Longitudinal fin along the full length of the intake; height = pipe diameter D.

6. Longitudinal fin along the full length of the intake; height = 2 x D

7. Longitudinal fin extending upstream from intake by 2 x D; height = D

8. Longitudinal fin extending upstream from intake by 2 x D; height = 2D

9. Roughening on floor of tank

10. Vertical cruciform, inside intake, finishing flush with face of outlet

11. Vertical cruciform, extending upstream from intake

12. Diagonal cruciform, extending upstream from intake

13. Square intake

The inhibitors are detailed in Figure 6.

The reasoning behind the choice of shape for the various inhibitors is summarised below.

Headwall

The aim was to simulate the conditions upstream from the face of the flush intake. The height was varied (width maintained constant) in order to determine how large it needed to be in order to produce a significant improvement in performance.

Longitudinal fin

The fin prevented flow across the intake axis, immediately behind the intake face. By shifting the effective boundary of the cross-flow away from the intake pipe, the rate of vorticity generation was decreased (because the general velocities decrease with distance from the immediate locality of the intake) and hence the severity of the vortex action was also decreased. Extending the fin forward of the intake face further reduced the rate at which vorticity was created.

Roughening of tank floor

In some of his experiments, Anwar roughened the floor of his cylindrical tank and found that the resulting vortices were much reduced in strength. In this series of experiments, the tank floor over an area around the intake, was roughened by adding 50mm cubes at 200mm centres.

Cruciform

An alternative to the hypothesis that the vorticity is generated by boundary shear, is that the vortex is formed by spiral flow in the intake itself and this feeds back into the main body of the approach flow, thus producing a vortex. The purpose of the cruciform was to straighten the flow in the intake and hence reduce any rotational influence upstream. Cruciforms both within the intake and extending upstream from it were tested.

Square intake

The effect of cross-sectional shape was investigated by using a square intake having the same flow area as the 200mm diameter pipe.

10 EXPERIMENTAL RESULTS FOR LARGE TANK

The results that have been obtained from the various inhibitors described in Section 9, are set out in Table 1. This shows the discharges at which the different bench mark phenomena were first observed to make an appearance, and the corresponding circulations measured from the float track photographs.

In order to simplify judgement of the effectiveness of the inhibitors, the discharge was selected as the appropriate parameter. The relative effectiveness of a particular inhibitor is gauged by the discharge ratio, defined as the discharge at which a particular phenomenon first appeared, divided by the discharge at which the same phenomenon first appeared with the original, plain, intake. The measured values of the discharge ratio are given in Table 2. Ratios greater than 1 indicate inhibitors that produce an improvement; less than 1, those that result in a worsenment. In many cases it was found that there was insufficient pump capacity on the rig, to allow the required flow phenomenon to be achieved.

All the inhibitors tested were successful in delaying the onset of surface dimples: in practically every case, the discharge ratio was greater than 1. There is quite a large range in the ratios, ranging from just over 1, to more than 4.85 for the fin of height 2D, with a water depth of 1.2m in the tank. Many of the inhibitors did not produce any improvement in the material drawdown and the air-core phases. A significant number had discharge ratios less than 1.

In order to be able to rank the various inhibitors in order of effectiveness, the mean of the three discharge ratios (one at each water level) was calculated for each of the three bench mark phenomena. The inhibitors were then ranked separately for each of the flow phenomena in turn, based on the calculated mean discharge ratios. The final overall ranking was determined by summing the three separate rankings for each inhibitor, weighting them in the ratio 3:2:1 (air core: material drawdown: dimple, assuming that inhibition of air core vortices is the most important attribute), and arranging them in order of increasing weighted ranking sum. If the same inhibitor were the most effective in coping with all three phases of vortex action, it would have a total score of 6. The final order (the most effective first) that emerged from this process was (with scores shown in parantheses):

Headwall 2.44m high	(8)
Extended fin, height 2D	(9)
Flush fin, height 2D	(22)

Headwall, 1.83m high	(30)
Headwall, 1.22m high	(40)
Headwall, 0.61m high	(43)
Square inlet	(44)
Extended cruciform	(47)
Extended fin, height D	(50)
Flush cruciform	(53)
Diagonal cruciform	(61)
Roughness board	(74)

Although the 2.44m high headwall was the most effective in delaying the onset of the various flow phenomena, it suffers from the severe disadvantage of massive size. The two fins, although not quite as effective as the large headwall, are much more compact.

The inertia of the large volume of water in the experimental tank meant that tests were proceeding only very slowly because sufficient time had to be allowed for any incipient vortex action to develop. In order to speed up the programme and allow a reasonable amount of testing to be carried out within the constraints of the financial budget, it was decided that further testing should be carried out in a smaller experimental tank.

11 SMALL EXPERIMENTAL TANK

A small tank was available, 1.83m square; this established a linear scale between the large and small tanks of 3.27:1. The small tank was fitted with a similar type of inlet manifold, and the principal features of the large tank were scaled down accordingly - the position of the baffling, and the geometry and location of the intake. The internal diameter of the intake was 63mm (corresponding to a scale ratio of 3.17 between the large and small intakes). The capacity of the pumping system was relatively larger than that on the big tank: the maximum discharge in the small tank was $0.024 m^3/s$, which when scaled according to the Froude criterion, was equivalent to $0.43 m^3/s$ in the big tank; this was over twice the discharge that it was actually possible to achieve there.

One feature possessed by the small tank but not the large one, was that two of its sides were of perspex, thus permitting close observation to be made of the sub-surface flow patterns.

12 BASE TESTS

The purpose of these tests (which corresponded to the initial tests in the large tank) was to establish the basic characteristics of the projecting intake.

The first essential was to ensure that the required types of vortex activity could be generated. It was here that one significant difference from the large tank experiments was noticed. In the large tank, it was necessary to blank off half the baffle screen in order to produce any significant vortex activity in the tank. In the small tank such measures were not necessary: air-core vortices were formed fairly readily. No explanation for this discrepancy is forthcoming: time and money did not permit any detailed pursuit of the cause of the different behaviour. Because all the testing is being carried out on a comparative basis, it was considered that the difference in the baffling arrangements would not influence the conclusions from the study. Photographs of an air-core vortex in the small tank are shown in Plates 4 and 5; a secondary counter-rotating vortex is also visible

Observations were made of the characteristics of the intake over the whole range of operating levels, with a discharge of $0.0106 m^3/s$ (equivalent to $0.19 m^3/s$ in the large tank). In general the vortex strengths in the small tank were weaker than in the big tank, particularly at the larger water depths. At low levels ($\frac{\text{submergence}}{\text{intake diameter D}} < 7.5$) there was reasonable agreement between the two sets of experiments: vortices of strength 5 or 6 were generated for $S/D < 5$, and of strength 4 or less for $7.5 > S/D > 5$.

When $S/D > 7.5$ the vortex strength in the small tank was weaker than in the large tank: 3 or 4 for $12.5 > S/D > 7.5$ compared with strengths of 5-6 in the large tank. For $S/D > 12.5$ the vortex strength dropped off in both tanks, but it fell to 1-2 in the small tank, compared with 2-4 in the large.

13 THRESHOLD DISCHARGES FOR PLAIN INTAKE

The threshold discharges were determined in the same manner as they were in the large tank. The water level in the tank was maintained constant and the discharge progressively increased until the various benchmark phenomena - dimple, material drawdown, or air core - appeared. Tests were carried out at water levels of 0.38, 0.57 and 0.79m.

When the small tank threshold discharges were compared with those from the big tank, it was found that they were relatively higher, after scaling up according to the Froudian scaling relationship for discharge. When the results from later tests on other entrance configurations were compared, the same trend was apparent. If the threshold discharges required for a particular phenomenon are compared, those for the large tank are generally 4 to 10 times those in the small tank, whereas if Froudian scaling applied, the ratio should be 17.9. This situation applied to both the air core and drawdown phases: in the dimple phase, the only divergence from this occurred in the tests at the maximum water level, where the discharge in the small tank was less than that predicted by Froudian scaling.

The immediate reaction is to assume that scale effects resulting from viscosity are affecting the results. However, it is by no means certain that this is the correct explanation. Jain's criterion (Eqs 16 and 19) leads to the conclusion that experiments on pipes of diameter less than 74mm will be subject to viscous effects. The diameter in the small tank was below this limit, but not so far below the limit that would lead to expectations of viscosity having a very large influence. Jain's submergence equation (18), indicates that, for the particular conditions in the small tank, the effect of viscosity will be to produce a change of 16 per cent in the critical submergence depth. However, if the same equation is used to determine the discharge corresponding to a critical submergence (assuming that the circulation remains constant), the effect of an intake diameter of 63mm is to require a threshold discharge three times that which would be required to produce a vortex with a 74mm intake diameter. In the Jain equation the discharge is very sensitive to the value of A_n.

Other researchers have produced different criteria for determining the limits for viscous effects. Chang [18] states that provided the intake diameter is greater than 61mm, viscous effects are not important.

Anwar gives as a limit, that the radial Reynolds number should be greater than 3×10^4. Applying this criterion to the results from the small tank show that viscous effects would have had an influence on the dimple thresholds at all water levels, the material drawdown threshold at the high level, and the air-core threshold at high level. The determination of the remaining thresholds would not be affected by viscosity.

14 TESTS ON INHIBITORS

A variety of intake configurations was tested: some of these were of similar design to those tested in the big tank, and were repeated for comparison purposes; others were completely new. A complete list of the configurations is as follows (see Figure 7):

1. Plain, projecting intake
2. Vertical headwall, flush with intake entrance
3. Vertical headwall, set back 100mm from entrance
4. Vertical headwall, set back 200mm from entrance
5. Vertical headwall, set back 300mm from entrance
6. Vertical headwall, set back 100mm, with fin on soffit
7. Headwall at 1 in 3 slope
8. Sloping headwall, at 80° to horizontal, flush with entrance
9. Sloping headwall, set back 100mm from entrance
10. Sloping headwall, set back 200mm from entrance
11. Fin on intake soffit, height D
12. Fin on intake soffit, height 2D
13. Series of individual fins on intake soffit, height 2D
14. Fin extended upstream from intake entrance height 2D
15. Square raft, side = D
16. Square raft, side = 3D/2
17. Square raft, side = 3D/2, with keel
18. Cruciform inside intake, finishing flush with face of outlet

19. Screen above intake
20. Vertical cord

The threshold discharges and circulations for all these inhibitors are set out in Table 3.

Even though the maximum discharge that could be supplied to the small tank was, relatively speaking, much larger than that which could be supplied to the large tank, it was still not possible, in some cases, to produce air-core vortices or material drawdown.

The method for assessing relative effectiveness was the same as that used for the large tank tests, viz ranking the inhibitors on the basis of the average discharge ratios, and then summing the weighted rankings.

Many of the inhibitors in the small tank tests were different from those tested in the previous experiments, so that direct comparison of the rankings is not valid. However, it is possible to compare some of the discharge ratios. The configurations that were tested in both tanks were the fins of height D and 2D, the extended fin and the cruciform. The average discharge ratios for each of the three threshold conditions are as follows:

	Dimple		Drawdown		Air-Core	
Type	small tank	large tank	small tank	large tank	small tank	large tank
Fin, height D	1.89	> 2.98	> 1.44	> 1.67	> 1.28	> 1.26
Fin, height 2D	1.35	1.41	1.24	1.01	1.17	> 1.06
Extended fin	2.09	> 2.35	> 1.61	> 1.92	> 1.40	> 1.53
Cruciform	1.50	1.89	1.69	1.09	> 1.33	> 0.90

When the discharge ratio is given as greater than a particular number, this implies that it was not possible to generate the particular phenomenon at all three water levels.

There are some differences between the results from the two series of experiments, but in some cases it is difficult to judge how significant the differences are. In other cases the agreement seems very reasonable, bearing in mind the subjectivity that is implicit in the experiments e.g. the point at which it is judged that the thresholds of the dimple or drawdown have been reached. Another factor is the randomness with which the phenomena seem to be generated: sometimes a particular condition can be created, which persists for some time before dying down, only to re-appear after a considerable period of time. On other occasions, phenomena appearing under certain conditions one day, could not be re-created under the same conditions the following day. Repeatability is thus difficult to achieve. Of the three phenomena, a continuous air core vortex is the one that is most easily and incontrovertibly recognised. However, the inability to generate this in every case means that it is not possible to be certain of the extent to which the discharge ratios are in agreement.

The overall rankings of the different inhibitors are as follows (total scores in parentheses):

Vertical headwall, flush	(6)
Vertical headwall, set back 100mm plus fin	(9)
Vertical headwall, set back 100mm	(10)
Sloping headwall at 80°, flush	(15)
Vertical headwall, set back 200mm	(18)
Sloping headwall, set back 100mm	(19)
Sloping headwall, set back 200mm	(42)

Vertical headwall, set back 300mm	(52)
Extended fin, height 2D	(61)
Individual fins, height 2D	(61)
Wall at 1 in 3 slope	(67)
Cruciform	(69)
Fin, height 2D	(79)
Raft, side D	(83)
Raft, side 3D/2	(83)
Fin, height D	(90)

The final ranking is similar, in many respects, to what might be expected. In the small tank, the headwalls extended the full width of the tank, not a relatively small part of the total width as was the case in the large tank. Thus, in the small tank, the vertical headwall, flush with the entrance, corresponds with the initial condition that was tested in the large tank, in which the intake was flush with the wall of the tank, and no vortices could be generated. As the headwall moves further and further back from the intake entrance, it approaches the initial condition for the small tank i.e. with the intake projecting some 500mm out from the wall.

The experiments with the headwalls demonstrate that, for the approach conditions adopted in the experiments, an intake, with its entrance flush with a headwall, will have a high threshold discharge for the generation of air-core vortices. The vertical and 80° headwalls are similar to the configurations that occur at concrete dams: the 1 in 3 slope is similar to that of an earth dam. The conclusion is that the smaller the projection of the intake from the headwall, the better is its performance as far as vortices are concerned.

In the experiments the approach conditions upstream from the intake remained constant, yet the results show that vortices became easier to generate as the intake projected further from the headwall. This suggests that local conditions to the intake have some influence on the vortex generation (this is in line with the model on which Sanmuganathan based his analysis [11]).

If, as is commonly argued, the general approach conditions also have an important bearing on vortex generation, it is very difficult, if not impossible, to specify, a type of vortex inhibitor that will be successful without carrying out model testing. It would be possible, on the basis of these experiments, to make some recommendations about an intake design, that would reduce the likelihood of any serious vortex activity. However, the general configuration of the site, at some distance from the intake, might itself generate circulation that would produce vortices.

The experiments that were carried out on modifications to the intake itself, showed that some of these (principally the fins) worked quite successfully. No reason can be given to explain the success of the fins in delaying the onset of the air-core vortex: they were equally successful in the experiments in both large and small tanks. One possible explanation is that they break up the local flow patterns around the entrance to the intake and thus make it more difficult to establish the comparatively coherent and well-ordered flow pattern of the vortex. The most successful of the fins were the one that extended upstream from the intake entrance and the one that was formed from a series of separate strips, staggered in plan, along the soffit of the intake. If judged solely on the effectiveness against air-core vortices, the fin formed from the strips was the best

Fins could only be employed, however, where the intake projected from the headwall. For cases where the intake entrance was flush with the headwall, other remedies are needed. For this reason rafts and submerged screens were also examined.

Rafts

Two sizes of raft were used in the tests: one with sides equal to the intake diameter D, the other with sides equal to 3D/2. The rafts were moored only loosely, in order to allow them to move almost at will over the water surface. The positioning of the raft was the most significant factor affecting its performance. When the raft was firmly located at the heart of the vortex it successfully prevented an air core from forming, even though it did not completely damp down the circulation. However, as the intensity of the vortex decreased there was, on occasion, a tendency for the raft to move out of the main vortex and be captured by the general flow in the tank. As the main vortex built up again gradually the raft was attracted back into the main vortex. A cyclic pattern of behaviour, although not of regular period, was thus set up.

Another difficulty with the raft was that the mooring line progressively became tangled, particularly when it was captured by the primary vortex and spun round a vertical axis. This tended to limit its freedom to move around.

In an attempt to assist the raft to remain in the primary vortex for longer periods, a small keel was added to it. This worked quite satisfactorily but the problems with the tangling mooring line still remained.

Although the discharge ratios for the rafts were not very large, they were more successful than the ratios indicate. When the rafts move out of the primary vortex, they do not have any inhibitory effect and the vortices are free to build up again. The threshold discharges are thus not greatly affected by them. What does change, however, is the proportion of time that air-core vortices occur: the rafts do reduce the total amount of strong vortex activity. Rafts have a number of advantages. They can be easily installed at the post-construction stage if vortices unexpectedly occur. They are cheap. They remain at the surface and so can readily respond to changes in water level, and to some extent they tend to be drawn into the vortex. Some consideration needs to be given to their mooring system - should they be free to move over a wide area or a very limited area? Should they be free to spin or should their angular movement be restricted?

Vertical cord

This was a development from the raft and was found to be very successful. It comprised a length of cord, approximately 2/3 of the depth of water, weighted at the lower end and fixed at the water surface, roughly above the face of the intake. As an air-core vortex started to grow, the cord was drawn to the vortex core and rotated by it. The result was that the cord cut across the vortex core and prevented it from building up into a continuous air core.

The advantage of this system compared with a raft is that the upper end of the cord remains anchored in position: the vortex seeking is done by the lower, free end of the cord, and so there is less chance of the inhibitor being side tracked by the attraction of a secondary vortex. It is a method that has many attractions. It is cheap, easily installed in the post-construction stage, and could possibly be made more effective by providing vanes to the cord that might increase the rate of energy dissipation in the vortex core.

Submerged screen

This consisted of a bar screen fixed horizontally above and projecting slightly in front of the face of the intake. This device does not prevent vortices building up at the water surface, but as the air core penetrates deeper below the surface it eventually passes through the screen, in order to enter the intake. Usually, the core does not remain in one position, and as a result of wandering across the bars of the screen it is cut off; it does not remain in any one position for a sufficient length of time for a stable air core to be established. Although the discharge ratio for the submerged screen is similar to that for the plain projecting pipe, the local conditions around the intake are quite different.

One weakness of the screen tested in these experiments was that the air core could enter the intake around the sides of the screen. This might be overcome if the screen were constructed in the form of a hooded canopy.

Although the screen is relatively simple to design and construct, it is not as easy to install as a raft or hanging cord, once a scheme has become operational.

15 PREDICTION OF THRESHOLD CONDITIONS

Many studies have been devoted to the study of vortices, and particularly to determining the critical submergence depth at which air core vortices will be generated for a particular set of hydraulic conditions.

A significant part of the experimental research from which these predictive methods have been derived, has been done on circular tanks in which the flow has been admitted around the periphery and the circulation generated by means of guide vanes or nozzles. By such means it has been possible to have circulation and discharge as two independent variables. In the experiments described in this report, discharge was the only variable: circulation was thus a dependent variable. Some of the data from the experiments described here, have been used to examine how generally applicable these predictive methods are.

Three methods have been selected for comparison, Jain [10], Sanmuganathan [11] and Amphlett [7]:

Jain. His submergence equation (18), when applied to the small tank can be simplified to:

$$S^{0.58} = 6.54\ \Gamma^{0.42}\ Q^{0.08} \text{ (metric units)}$$

For the large tank, the equation becomes:

$$S^{0.58} = 5.34\ \Gamma^{0.42}\ Q^{0.08} \text{ (metric units)}$$

In plotting these equations the assumption has been that they are being used to determine the circulation required to form an air-core vortex for particular combinations of discharge and submergence. The plot for the large tank, together with the appropriate experimental data, is shown in Figure 8. The corresponding plot for the small tank is shown in Figure 9.

Although it can be seen from Figure 8 that the data plot above the appropriate critical circulation line, nevertheless the agreement is not too bad. The data for the small tank show a very much greater divergence from the theoretical line, even though the Jain equation does include an allowance for viscous effects. The experimental results indicate that, for the small tank, a much greater circulation is required to create an air-core vortex than Jain predicts. The Jain criterion appears to err on the conservative side.

Another interesting feature of the plots is that Jain's equation suggests that as the discharge increases, the circulation required to form a vortex remains practically constant. The suggestion from the plots of the experimental data is that, for a given water level, as the threshold discharge increases, so does the threshold circulation.

Sanmuganathan. His prediction of the onset of air-core vortices depends on the region of an α-β plot in which the experimental data points plot. α is a dimensionless coefficient reflecting the influence of discharge; β is a dimensionless coefficient reflecting the influence of circulation. The α-β values, corresponding to the threshold experimental conditions, plot well down in the vortex-free region. There appears to be no obvious explanation for the marked discrepancy between the predicted and the experimental thresholds, particularly as the Anwar and Amphlett experimental data had been used to evaluate one of the unknown variables.

Anwar. He produced two graphical relationships between dimensionless groups, reflecting the influence of submergence, circulation and discharge. The dimple and air-core experimental data have been plotted in terms of these dimensionless groups, with data from the large and small tanks plotted on the same graph. On the whole, the data seem to be in good agreement with the threshold criterion delineated on the plot of $\Gamma D/Q$ vs $Q/\nu S$ (Figure 10).

16 DISCUSSION OF THRESHOLD PREDICTIONS

Much of the work on threshold conditions, particularly for vertical intakes, has been based on experiments in circular tanks, with the intake located on the vertical axis of the tank. The present work on vortex inhibitors has indicated that the threshold discharge is a function of the intake geometry; this implies that there is no unique threshold relationship that can be used for all vertical or for all horizontal intakes. On the contrary, the threshold relationship is a unique function of the intake geometry and of the structure of the flow approaching the intake. The curves derived by Anwar or Jain (say) should thus only be applied to conditions that are similar to those under which the original experiments were carried out.

Although the prediction methods present the relationship between the pertinent dimensionless groups as a continuous function, in many, if not most, cases this will not be a true reflection of the actual situation. The continuous function will only apply if the circulation can be varied independently of the discharge, for a given submergence depth.

In many cases, the circulation will not be an independent parameter, but will depend on the discharge and the configuration of the intake and its surrounds. Thus if an air-core vortex occurs for a particular discharge and submergence, it would not be possible to change the discharge, whilst maintaining the same submergence, and produce another threshold condition. The threshold condition for many intakes will thus comprise a series of points, each point representing the threshold discharge for a particular submergence depth.

When the inhibitor data are plotted in terms of the Anwar parameters $\Gamma D/Q$ and $Q/\nu S$, the threshold condition for an air-core vortex plots over a fairly narrow range of Kolf numbers (i.e. $\Gamma D/Q$) - mainly from 0.065 to 0.155, despite the data covering many types of intakes, three different water levels, and experiments in both large and small tanks. Unfortunately, because of the limitations on the discharge that could be pumped through each rig, it was not possible to get complete sets of data on the inhibitors that were tested in both tanks. Several limited sets of data were obtained for the original, plain intake and for the fins height D and 2D. The values of Kolf number at the air-core threshold are shown below:

	Water depth in large tank (m)			Water depth in small tank (m)		
Type	1.2	1.8	2.4	0.38	0.57	0.79
Original	97.2×10^{-3}	34.3×10^{-3}	99.9×10^{-3}	99.3×10^{-3}	96.8×10^{-3}	96.9×10^{-3}
Fin, D	68.4×10^{-3}	-	-	100.4×10^{-3}	68.6×10^{-3}	87.9×10^{-3}
Fin, 2D	79.3×10^{-3}	-	-	77.9×10^{-3}	67.9×10^{-3}	-

Of these results, those for the original intake in the large tank at the intermediate level and the 2D fin in the small tank at the low level are doubtful. In both cases the circulation is out of line with the circulations measured in the other tests on the same intake. If these doubtful results are neglected, there is a reasonable constancy in the Kolf numbers for a particular intake. The mean values are:

Original	98.0×10^{-3}
Fin D	75.0×10^{-3}
Fin 2D	75.0×10^{-3}

If this result is generally true viz that at the threshold condition the Kolf number is constant and isindependent of the radial Reynolds number, it means that the threshold condition for a particular submergence depth cannot be determined from Figure 10 alone. Some other relationship is required in order to be able to determine the critical submergence. If the relationship between circulation and discharge was a function of water depth (for a given intake geometry), then this would provide a solution path. The experimental data for the three types of intake show that there are different relationships between Γ and Q for the large and small tanks. The results from the small tank suggest that the different intakes do produce different Γ-Q relationships, but that the data for different submergences could all collapse on to one curve. On the other hand if individual regression lines are fitted to the data from the tests at each of three water levels for one intake, threshold discharges can be predicted. The predicted threshold discharges for the three water levels, are as follows (measured threshold discharges in parentheses): $.0028m^3/s$ ($.0154m^3/s$), $.0175m^3/s$ ($.017m^3/s$), $.025m^3/s$ ($.023m^3/s$). Further data are needed in order to confirm whether this procedure is valid.

17 CONCLUSIONS

Experiments have been carried out on a variety of intakes in order to assess their effectiveness in suppressing vortex action, particularly the onset of air-core vortices.

Two basic sizes of intake were used in the tests, each of which was tested in its own tank: the ratios of similar dimensions of the two tanks were almost identical to the ratios of the intake diameters that they contained, in order to eliminate geometric scale effects.

Several of the intake designs were tested in both tanks, and it was observed that the discharges required to generate particular types of vortex in the small tank were much larger (when scaled up according to the Froudian scale relationship) than the corresponding discharges in the large tank. Another discrepancy between the two tanks was that different screen arrangements were required in the two tanks in order to produce air entraining vortices.

The various intake arrangements were found to have an effect on threshold discharges. Intakes that performed satisfactorily in the big tank experiments, also performed well in the small tank.

The tests that were carried out on different types of headwall showed that the most effective arrangement was with the face of the intake flush with the headwall. As the headwall was moved back from the intake face, the threshold discharge progressively reduced.

Where the face of the intake projects well out from a headwall, those arrangements incorporating a fin along the soffit of the intake were found to be the most effective.

The view has been advanced that vortices can be generated either by conditions at the intake or by conditions more remote from it. Thus even if the intake were flush mounted in the most effective type of headwall, the inception of vortices could not be ruled out. In such circumstances, there is little freedom to modify the intake itself. There are several possible solutions that tests showed to be quite effective: these were rafts, vertical cord, andsubmerged screen. These, although not preventing the formation of a strong vortex at the water surface, did strangle the sub-surface air core and prevented it from becoming permanent. Further testing of these devices is required.

Various criteria for predicting threshold conditions were examined in the light of the experimental data, and that developed by Anwar was found to give reasonable agreement. Because there were only a few complete sets of data, it was not possible to make an exhaustive analysis of Anwar's method. What data there were, suggested that at the threshold of air-core formation the Kolf number ($\Gamma D/Q$) was constant and the same for both tanks. If this is the case, an additional relationship is required in order to solve the threshold condition, and it is possible that this could be provided by the relationship between circulation and discharge, which may be a function of the submergence. Further work is required to verify this.

18 RECOMMENDATIONS FOR FURTHER RESEARCH

There are a number of promising avenues for further research; they are, in outline, as follows:

(a) Further measurements to investigate whether the relationship between discharge and circulation is a function of intake geometry and submergence depth. Also to investigate whether the Kolf number can be assumed to be constant for the threshold conditions for a particular intake.

(b) To investigate the effect of vortex formation on the pressure distribution within an intake and on its coefficient of discharge.

(c) To study alternative geometries for the submerged screen type of inhibitor.

(d) To study the feasibility of the vertical cord type of inhibitor, and to develop a more effective method of mooring for the floating raft inhibitor.

The Department of the Environment has agreed to provide further funding for research on vortex inhibitors and this will enable work to be done on some of the aspects listed above.

19 ACKNOWLEDGEMENTS

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Department Head: Dr W R White
Section Leader : J A Perkins

The major part of the experimental work has been done by I WIlloughby, who has shown much patience and has sustained careful observation over a long period. The large experimental tank was designed and calibrated by A D Crabbe.

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TABLES

Table 1: Values of (a) Threshold Discharge (m^3/s) (b) Circulation (m^2/s): Large tank

Vortex type	Water depth: m	Plain pipe projecting	Headwall 0.61m	Headwall 1.22m	Headwall 1.83m	Headwall 2.44m	Roughness Board	Flush Fin; height 2D	Extended fin; height 2D	Flush Fin; height D	Extended fin; height D	Flush Cruciform;	Extended Cruciform;	Diagonal Extended cruciform	Square Intake
Dimple	1.2 (a)	0.022	0.031	-	0.030	0.043	0.025	0.038	0.045	0.039	0.037	0.051	0.030	0.043	0.034
	(b)	No data	0.0110	-	0.0165	0.0161	0.0137	0.0096	0.0034	0.0046	0.0124	0.0109	0.0190	0.0169	0.0097
	1.8 (a)	0.0423	0.080	0.079	0.075	0.100	0.048	>0.205	0.106	0.052	0.061	0.090	0.101	0.107	0.048
	(b)	0.0062	0.0146	No Data	0.0214	0.0144	0.0071	No data	0.0312	0.0135	0.0083	0.0090	0.0186	0.0283	0.0152
	2.48(a)	0.086	0.093	0.083	0.089	0.146	0.114	>0.205	>0.205	0.109	0.096	0.104	0.091	0.082	0.097
	(b)	0.0278	0.0191	0.0209	0.0069	0.0161	0.0152	No data	No data	0.0118	No data	0.0323	0.0171	0.0151	0.0075
Material drawn down	1.2 (a)	0.0425	0.057	-	0.063	0.168	0.043	0.092	0.125	0.065	0.076	0.058	0.061	0.059	0.061
	(b)	0.0229	0.0324	-	0.0226	0.0814	0.0310	0.0295	0.0537	0.0133	0.0441	0.0370	0.0341	0.0408	0.0279
	1.8 (a)	0.1362	0.115	0.154	0.109	0.127	0.098	>0.205	>0.205	0.100	0.105	0.111	0.109	0.115	>0.205
	(b)	0.0180	0.0389	0.0573	0.0417	0.0428	0.0332	No data	No data	0.0193	0.0415	0.0424	0.0427	0.0560	No data
	2.48(a)	0.157	0.165	0.154	>0.205	>0.205	>0.205	>0.205	>0.205	0.121	0.145	0.172	0.168	0.136	>0.205
	(b)	0.0540	0.0524	0.0434	No data	No data	No data	No data	No data	0.0226	0.0579	0.0660	0.0497	0.0778	No data
Air-core	1.2 (a)	0.0856	0.115	>0.205	0.162	>0.205	0.067	0.136	>0.205	0.083	0.085	0.065	0.079	0.077	0.069
	(b)	0.0416	0.0726	No data	0.0641	No data	0.0494	0.0539	No data	0.0286	0.0474	0.0441	0.0480	0.0489	0.0545
	1.8 (a)	0.180	0.176	>0.205	>0.205	>0.205	0.130	>0.205	>0.205	>0.205	0.157	0.155	0.177	0.139	>0.205
	(b)	0.0328	0.0667	No data	No data	No data	0.0661	No data	No data	No data	0.0775	0.0704	0.0663	0.0621	No data
	2.48(a)	0.1926	0.183	>0.205	>0.205	>0.205	>0.205	>0.205	>0.205	>0.205	>0.205	>0.205	>0.205	0.178	>0.205
	(b)	0.0962	0.0773	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	0.1271	No data

>0.205 indicates that the particular vortex type could not be produced for that combination of water depth and intake geometry

Table 2: Discharge ratios: Large tank

Type		Dimple			Drawdown			Air-core		
	Water depth:m	1.2	1.8	2.48	1.2	1.8	2.48	1.2	1.8	2.48
Original intake		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Headwall, 0.61m high		1.41	1.90	1.03	1.34	0.85	1.05	1.34	0.98	0.95
Headwall, 1.22m high		–	1.64	0.96	–	1.07	0.91	>2.39	>1.14	>1.06
Headwall, 1.83m high		1.46	1.77	1.03	1.48	0.80	>1.31	1.89	>1.14	>1.06
Headwall, 2.44m high		1.93	2.36	1.69	3.96	0.93	>1.31	>2.39	>1.14	>1.06
Roughness board		1.13	1.12	1.32	1.02	0.72	>1.31	0.80	0.73	>1.06
Fin, height 2D		1.71	>4.85	>2.38	2.19	>1.51	>1.31	1.59	>1.14	>1.06
Fin, height D		1.75	1.22	1.27	1.54	0.73	0.77	0.97	>1.14	>1.06
Extended fin, height 2D		2.1	2.52	>2.38	2.93	>1.51	>1.31	>2.39	>1.14	>1.06
Extended fin, height D		1.69	1.44	1.12	1.80	0.77	0.93	0.99	0.88	>1.06
Cruciform		2.33	2.12	1.21	1.36	0.81	1.09	0.77	0.86	>1.06
Extended cruciform		1.37	2.40	1.06	1.44	0.80	1.07	0.92	0.99	>1.06
Diagonal cruciform		1.95	2.53	0.94	1.38	0.84	0.86	0.90	0.78	0.93
Square inlet		1.53	1.15	1.13	1.44	>1.51	>1.31	0.80	>1.14	>1.06

Table 3: Values of (a) Threshold Discharge (m^3/s) (b) Circulation (m^2/s): Small tank

Vortex type	Water depth: m		Plain pipe projecting	Vertical Headwall Flush	Vertical Headwall (100mm back)	Vertical Headwall (100mm back and Fin Height D)	Vertical Headwall (200mm back)	Vertical Headwall (300mm back)	Headwall at 1 in 3 slope	Sloping (80°) Headwall Flush	Sloping (80°) Headwall (100mm back)	Sloping (80°) Headwall (200mm back)	Flush Fin Height 2D	Flush fin Height D	Extended Fin Height 2D	Series of individual Fins Height 2D	Raft 'D' square	Raft '3/2D' square	Raft '3/2D' square with keel	Cruciform flush	Screen above intake 'D' Square
Dimple	0.382	(a)	0.0023	0.0141	0.0122	0.0128	0.0092	0.0082	0.0075	0.0090	0.0082	0.0075	0.0046	0.0045	0.0069	0.0063	0.0074	0.0080	0.0070	0.0040	0.0059
		(b)	0.0041	0.0054	0.0059	0.0098	0.0036	0.0088	0.0077	0.0040	0.0040	0.0055	0.0037	0.0048	0.0076	0.0071	0.0102	0.0078	0.0074	0.0080	0.0059
	0.573	(a)	0.0067	0.0169	0.0162	0.0167	0.0126	0.0146	0.0082	0.0158	0.0129	0.0108	0.0089	0.0072	0.0113	0.0111	0.0144	0.0106	0.0100	0.0086	0.0085
		(b)	0.0051	0.0065	0.0085	0.0037	0.0025	0.0170	0.0036	0.0043	0.0033	0.0054	0.0109	0.0077	0.0069	0.0108	0.0108	0.0103	0.0043	0.0049	0.0057
	0.795	(a)	0.0077	> 0.0263	> 0.0263	> 0.0263	0.0207	0.0118	0.0117	0.0182	0.0160	0.0185	0.0179	0.0082	0.0123	0.0116	0.0125	0.0112	0.0127	0.0117	0.0116
		(b)	0.0059	No data	No data	No data	0.0058	0.0037	0.0068	0.0072	0.0047	0.0063	0.0078	0.0076	0.0112	0.0115	0.0070	0.0102	0.0112	0.0064	0.0066
Material drawn down	0.382	(a)	0.0121	> 0.0263	0.0245	0.0245	0.0211	0.0146	0.0137	0.0220	0.0209	0.0193	0.0135	0.0125	0.0159	0.0126	0.0135	0.0122	0.0121	0.0143	0.0141
		(b)	0.0159	No data	0.0173	0.0131	0.0205	0.0170	0.0163	0.0097	0.0107	0.0121	0.0145	0.0123	0.0240	0.0176	0.0170	0.0154	0.0151	0.0145	0.0141
	0.573	(a)	0.0127	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	0.0239	> 0.0263	> 0.0263	> 0.0263	0.0178	0.0162	0.0216	> 0.0263	0.0196	0.0200	0.0168	> 0.0263	0.0160
		(b)	0.0221	No data	No data	No data	No data	No data	0.0135	No data	No data	No data	0.0184	0.0233	0.0240	No data	0.0173	0.0212	0.0147	No data	0.0125
	0.795	(a)	0.0146	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	0.0205	> 0.0263	0.0234	0.0170	0.0229	0.0203	> 0.0263	0.0211
		(b)	0.0215	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	0.0261	No data	0.0353	0.0189	0.0261	0.0198	No data	0.0174
Air core	0.382	(a)	0.0154	> 0.0263	> 0.0263	> 0.0263	> 0.0263	0.0199	0.0191	> 0.0263	> 0.0263	0.0233	0.0159	0.0158	0.0199	0.0216	0.0154	0.0143	0.0149	0.0166	0.0172
		(b)	0.0242	No data	No data	No data	No data	0.0246	0.0308	No data	No data	0.0196	0.0197	0.0251	0.0320	0.0300	0.0238	0.0221	0.0228	0.0209	0.0228
	0.573	(a)	0.0170	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	0.0242	0.0241	> 0.0263	> 0.0263	0.0232	0.0222	0.0229	> 0.0263	0.0243
		(b)	0.0261	No data	No data	No data	No data	No data	No data	No data	No data	No data	0.0261	0.0262	No data	No data	0.0298	0.0207	0.0230	No data	0.0213
	0.795	(a)	0.0232	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	> 0.0263	0.0243	> 0.0263	> 0.0263	0.0230	> 0.0263	> 0.0263	> 0.0263	> 0.0263
		(b)	0.0357	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	0.0339	No data	No data	0.0245	No data	No data	No data	No data

> 0.0263 indicates tht the particular vortex type could not be produced for that combination of water depth and intake geometry

Table 4: Discharge ratios: Small tank

Type	Dimple			Drawdown			Air core		
Water depth:m	0.382	0.573	0.795	0.382	0.573	0.795	0.382	0.573	0.795
Original intake	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Headwall, flush	6.09	2.52	>3.43	>2.17	>2.08	>1.80	>1.71	>1.55	>1.37
Headwall, set back 100mm	5.24	2.41	>3.43	2.02	>2.08	>1.80	>1.71	>1.55	>1.37
Headwall, set back 200mm	3.98	1.88	2.69	1.74	>2.08	>1.80	>1.71	>1.55	>1.37
Headwall, set back 300mm	3.54	1.61	1.53	1.21	>2.08	>1.80	1.30	>1.55	>1.37
Headwall, set back 100mm with fin D	5.51	2.49	>3.43	2.02	>2.08	>1.80	>1.71	>1.55	>1.37
Extended fin, height 2D	2.98	1.68	1.60	1.31	1.71	>1.80	1.29	>1.55	>1.37
Fin, height 2D	1.99	1.33	2.34	1.11	1.41	>1.80	1.04	1.43	>1.37
Fin, height D	1.92	1.07	1.06	1.03	1.28	1.40	1.03	1.42	1.05
Cruciform	1.70	1.28	1.53	1.18	>2.08	>1.80	1.08	>1.55	>1.37
Headwall at 1 in 3 slope	3.25	1.33	1.52	1.13	1.88	>1.80	1.25	>1.55	>1.37
Series of small, individual fins, height 2D	2.71	1.65	1.52	1.04	>2.08	1.60	1.41	>1.55	>1.37
Headwall at 80° to horizontal: flush	3.88	2.35	2.38	1.81	>2.08	>1.80	>1.71	>1.55	>1.37
Headwall at 80° to horizontal: set back 100mm	3.55	1.92	2.09	1.72	>2.08	>1.80	>1.71	>1.55	>1.37
Headwall at 80° to horizontal: set back 200mm	3.25	1.61	2.42	1.59	>2.08	>1.80	1.52	>1.55	>1.37
Raft, side D	3.20	2.15	1.62	1.11	1.55	1.16	1.00	1.36	0.99
Raft, side 3D/2	3.45	1.58	1.46	1.00	1.58	1.57	0.93	1.31	1.13

FIGURES

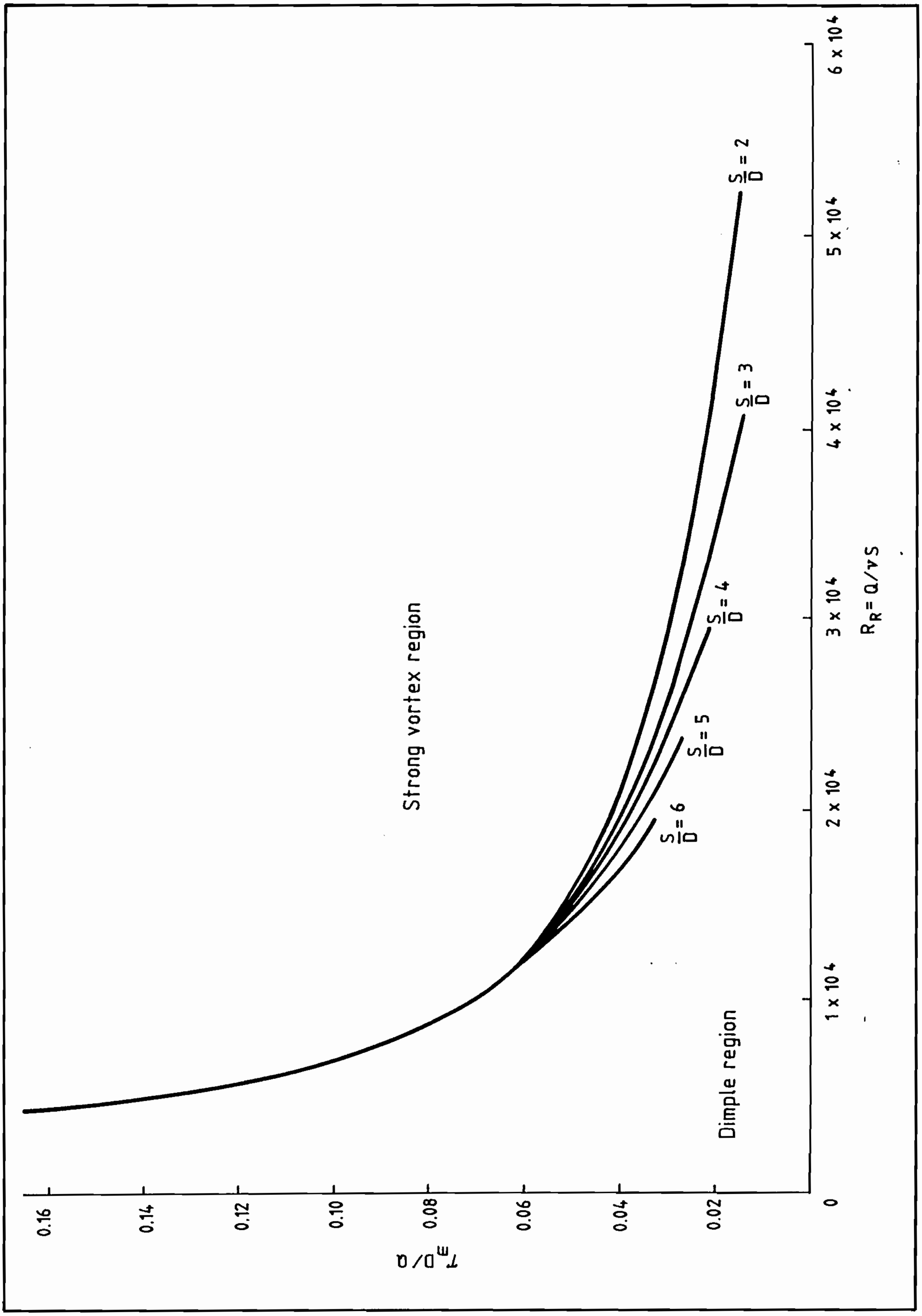


Fig. 1 Circulation parameter as a function of radial Reynolds number and submergence

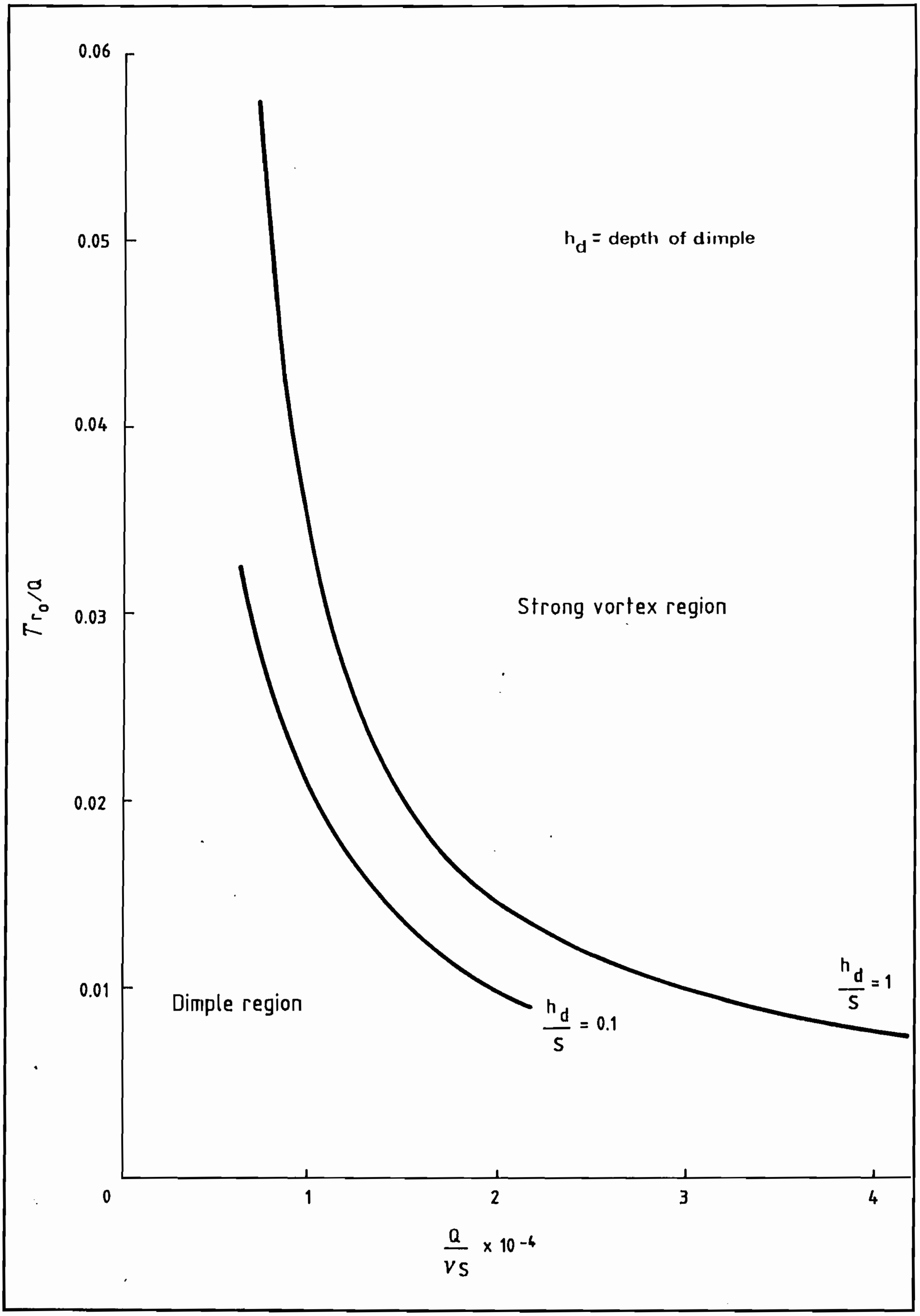


Fig. 2 Threshold conditions for vortex with dimple and air core

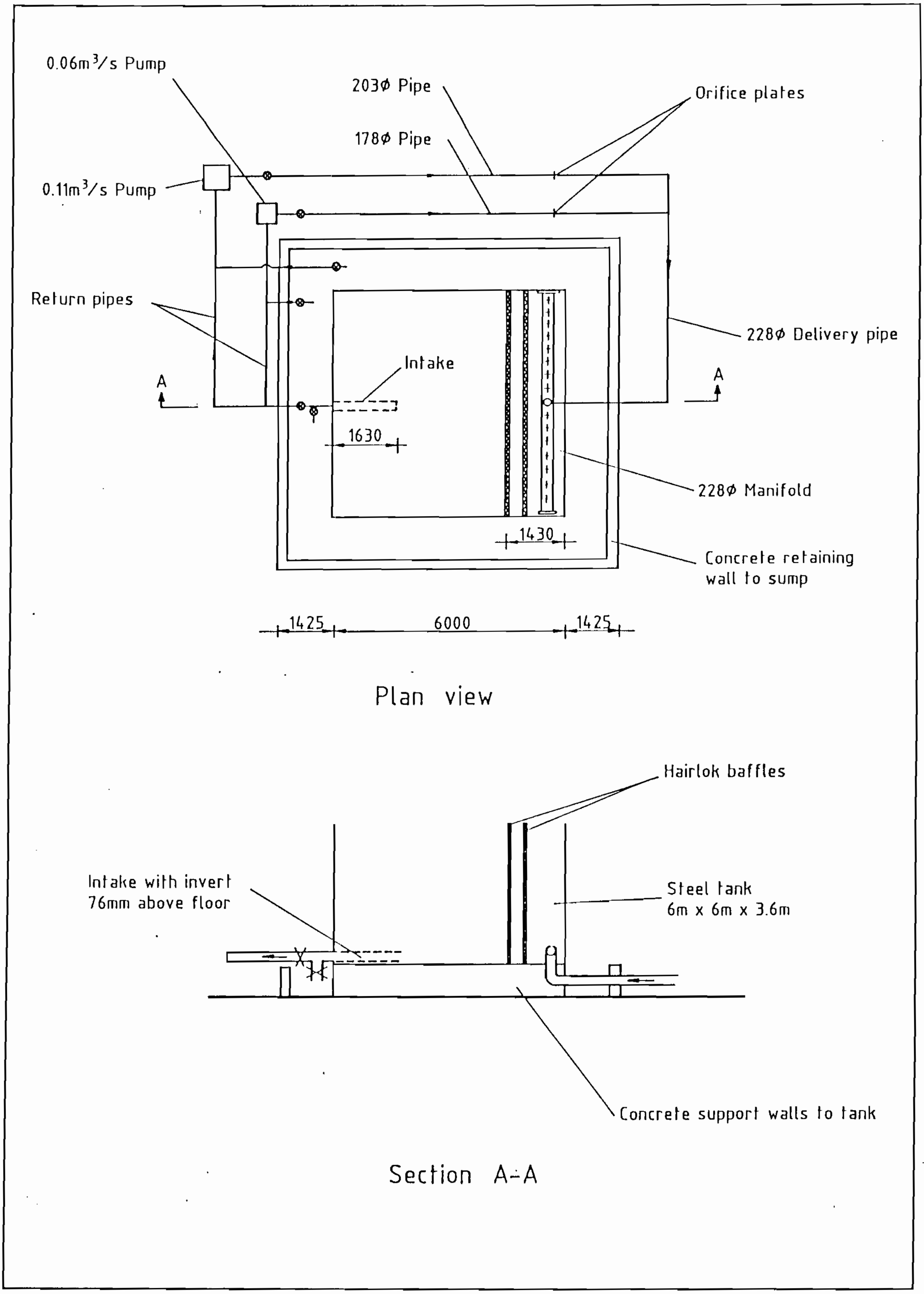


Fig. 3 General layout of large experimental tank

Vortex strength scale

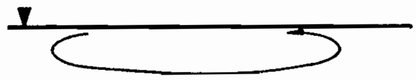
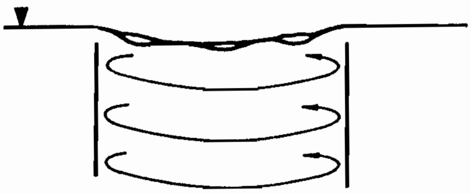
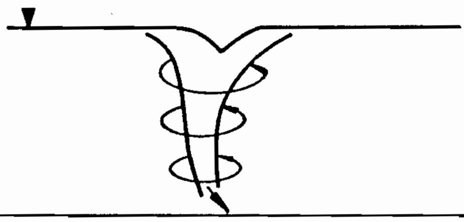
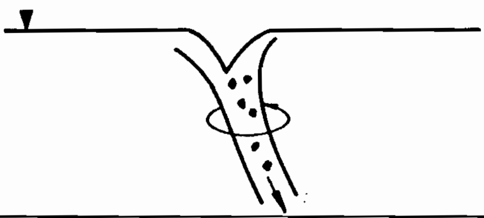
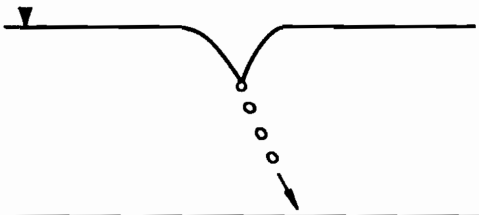
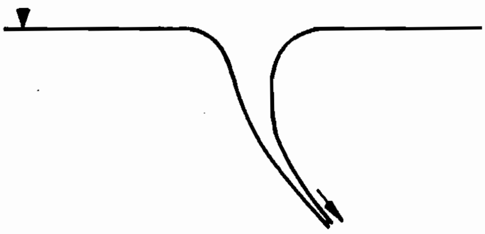
1		Surface rotation
2		Surface depression with minor dimples. Rotating column of water without significant draw to intake.
3		Surface dimple. Rapidly rotating narrow water core with draw to intake.
4		Draw of water and floating trash to intake.
5		Draw of air bubbles to intake.
6		Open air core with continuous air entrainment.

Fig. 4 Vortex strength classification

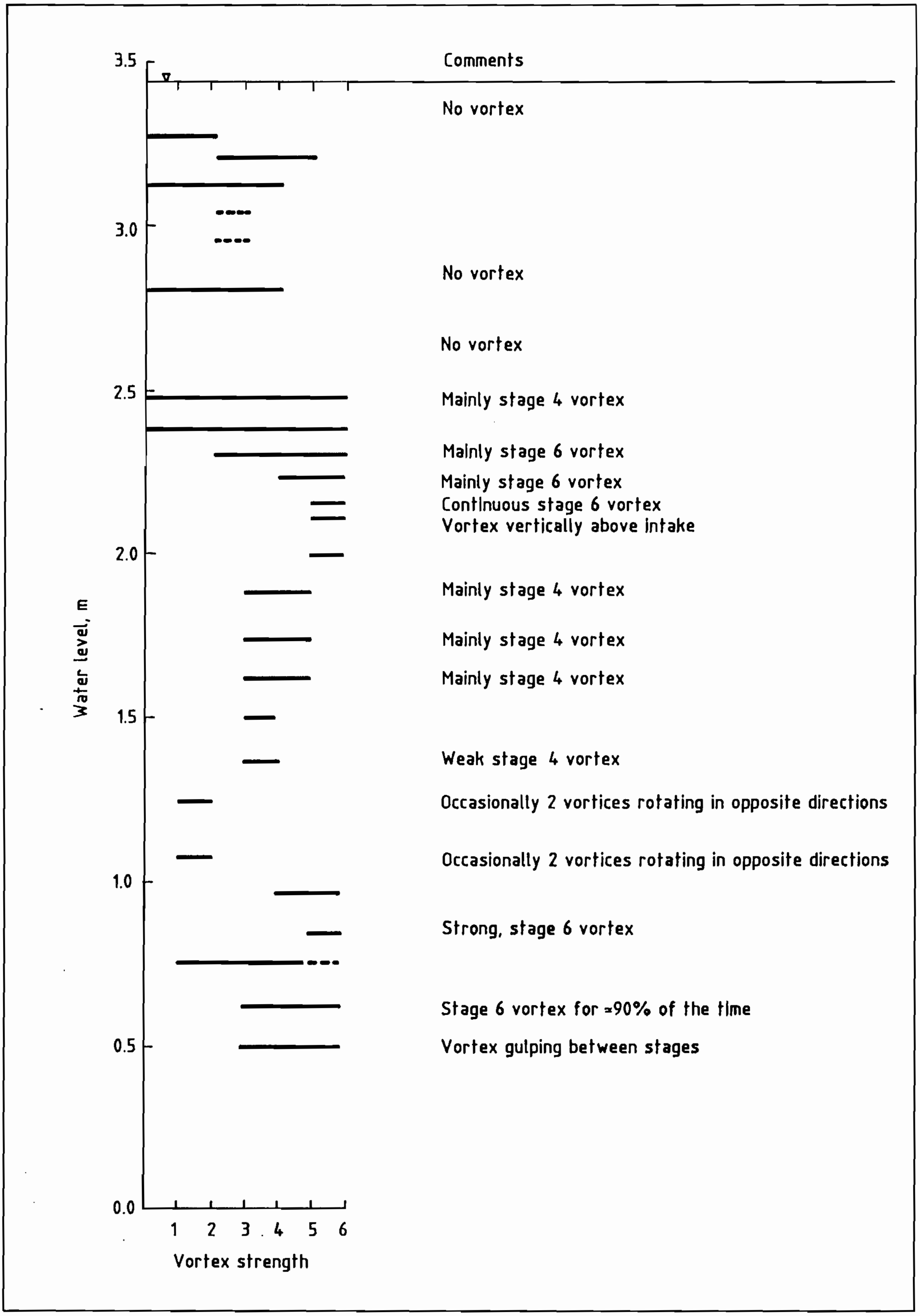
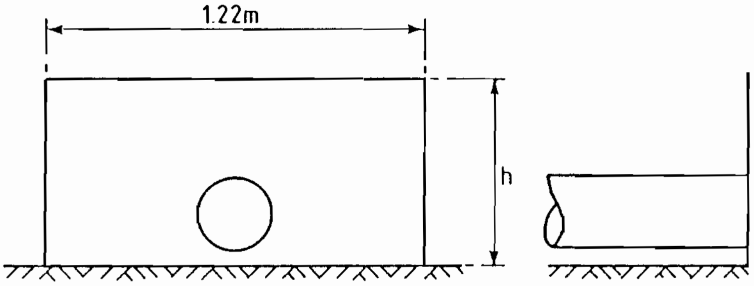
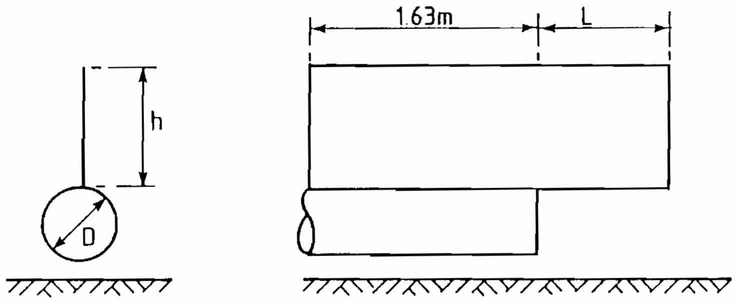


Fig. 5 Variation of vortex strength with water level : projecting intake



Headwall

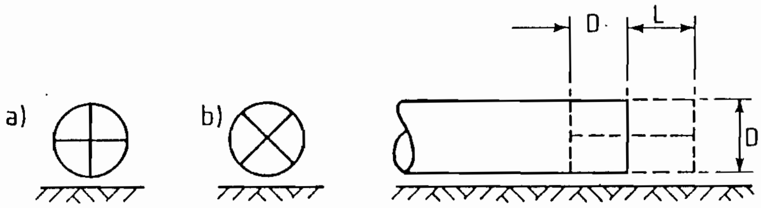
Tests carried out with h = 0.61, 1.22, 1.83 and 2.44m respectively



Fin

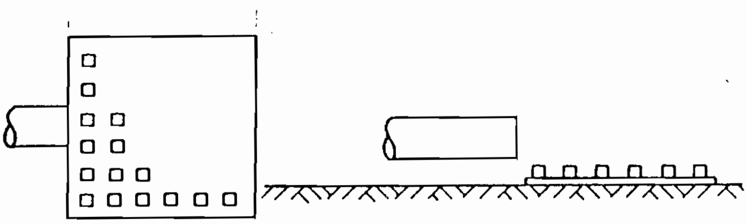
Tests carried out for

h	L
D	0
D	D
2D	0
2D	2D



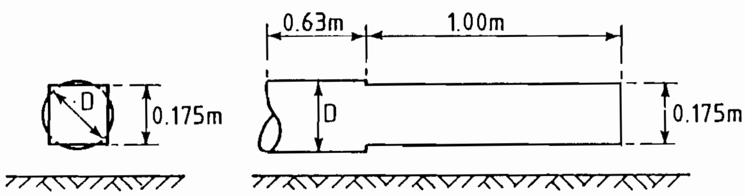
Cruciform

Type a) with L = 0,D
Type b) with L = D



Roughness

Cubes of 50mm side fixed at 200mm centres on base-board 1.22m square



Square section intake

Fig. 6 Types of inhibitor : Large tank

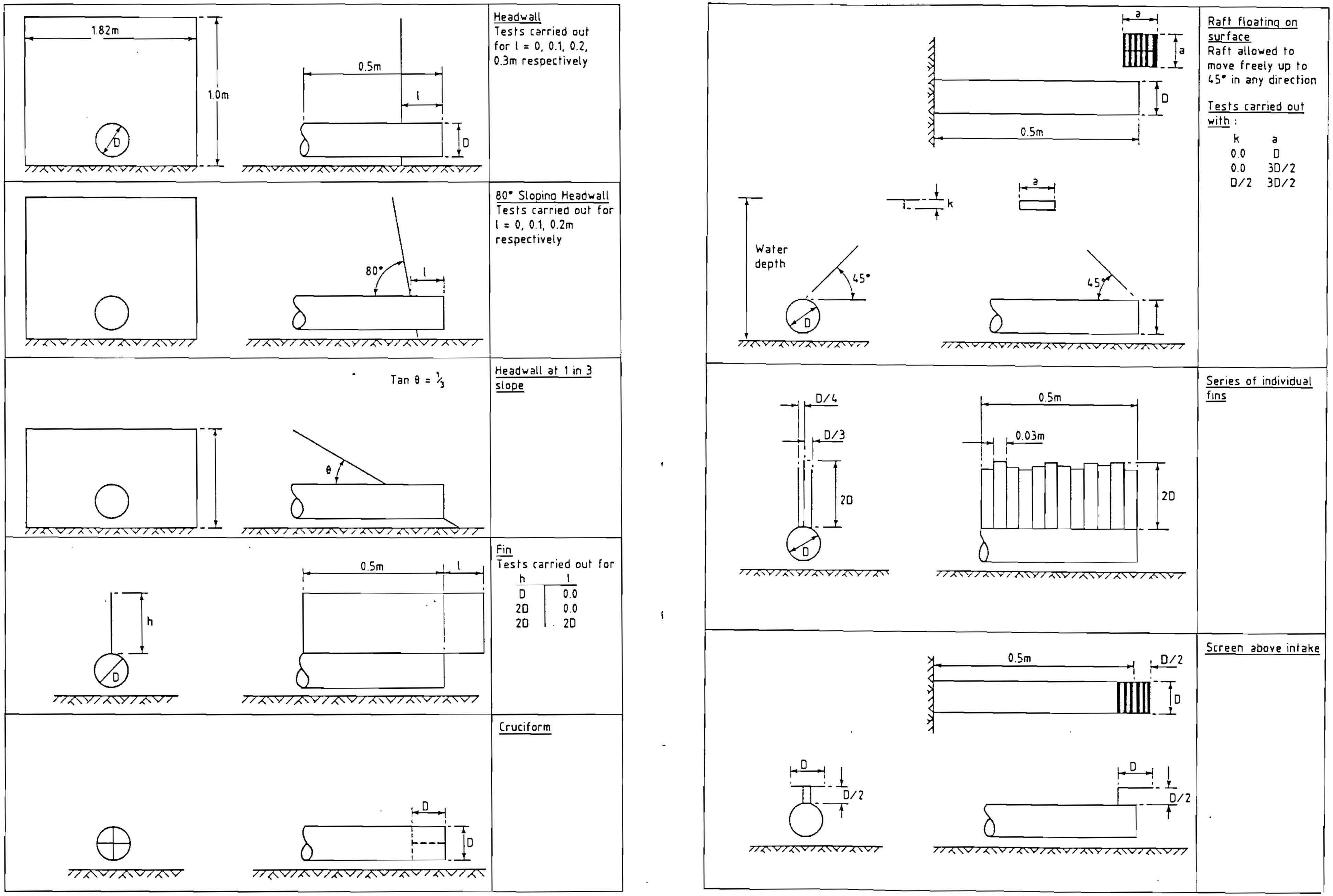


Fig 7 Types-of-inhibitor : Small tank

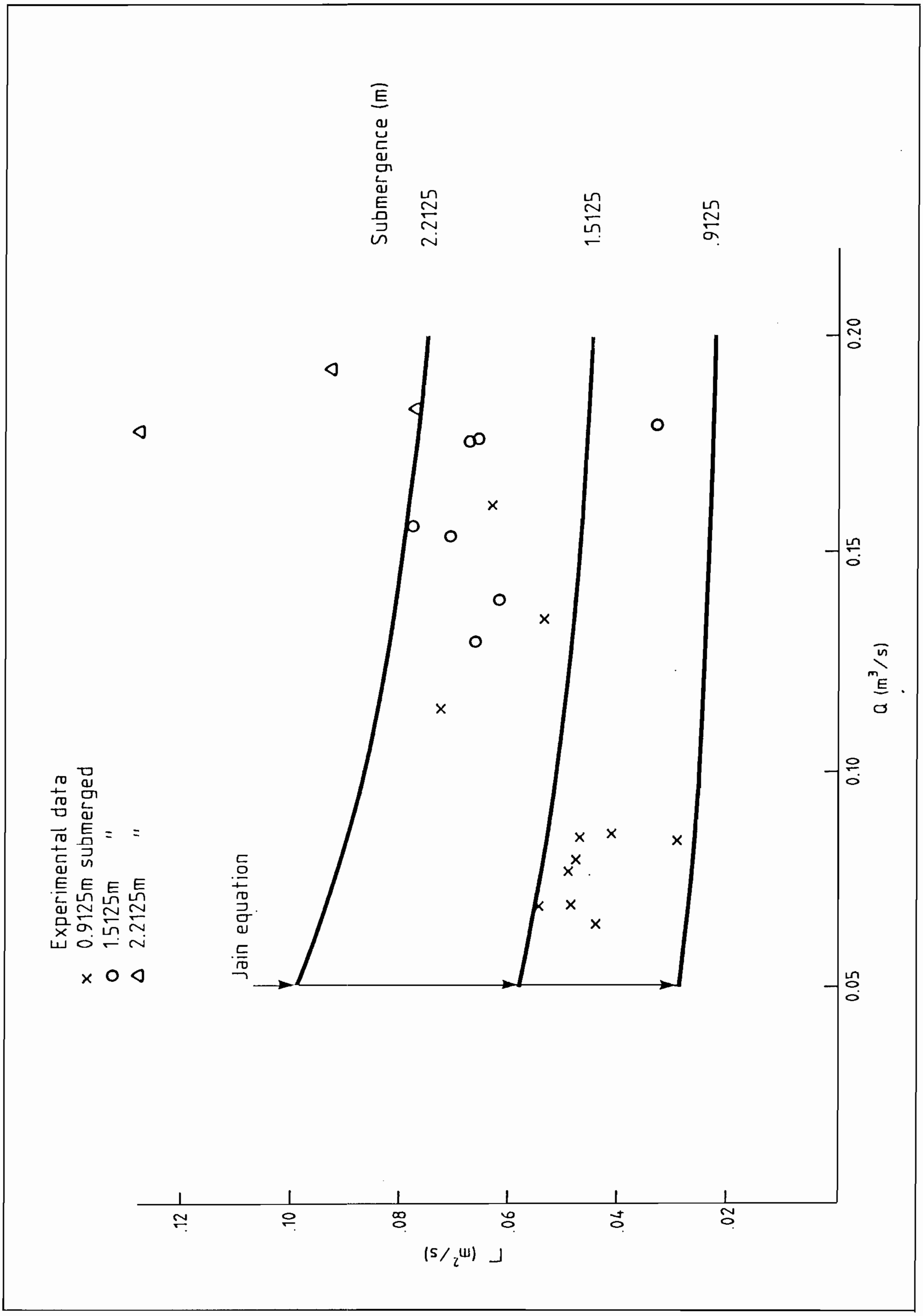


Fig 8 Threshold conditions for large tank

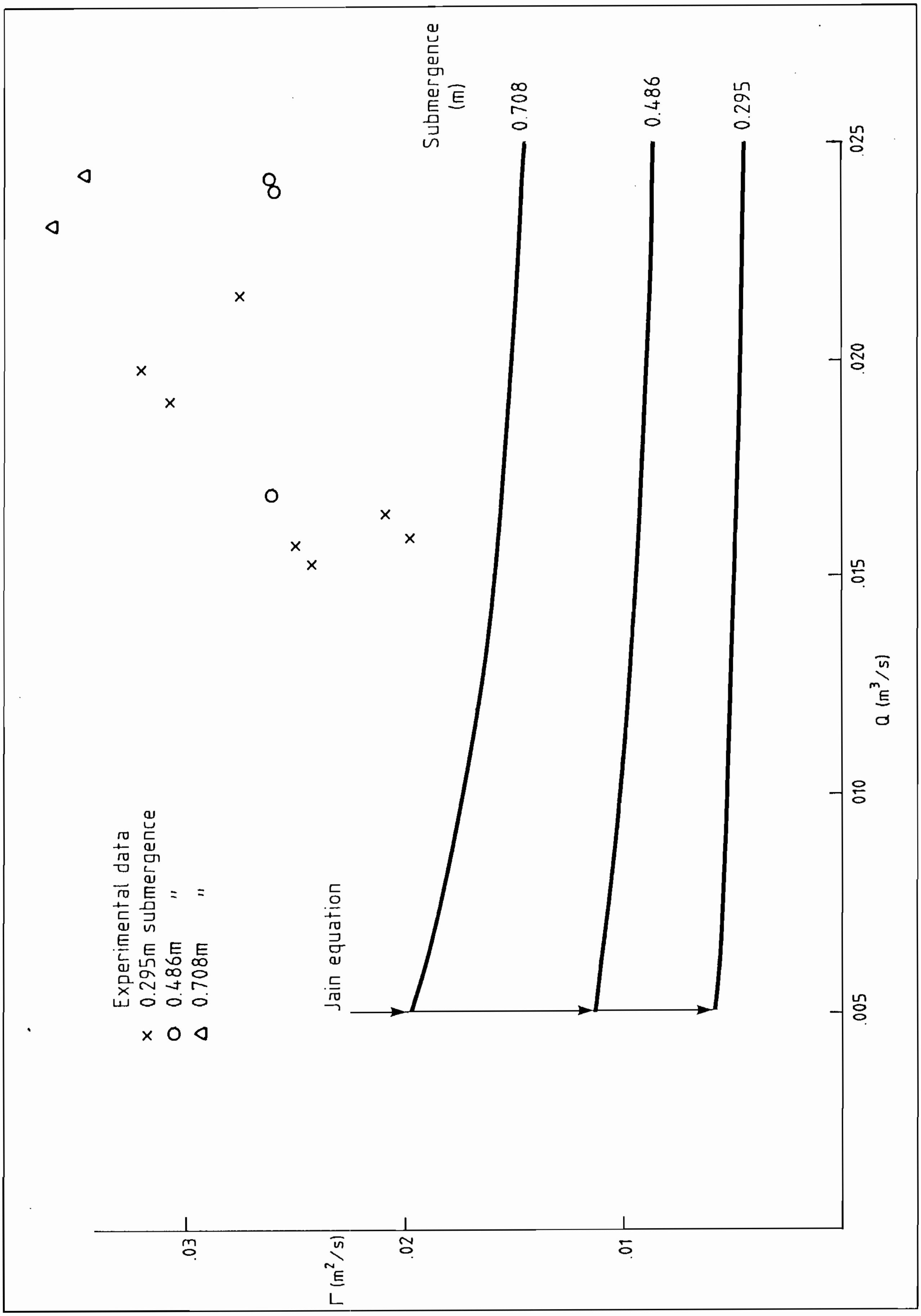


Fig 9 Threshold conditions for small tank

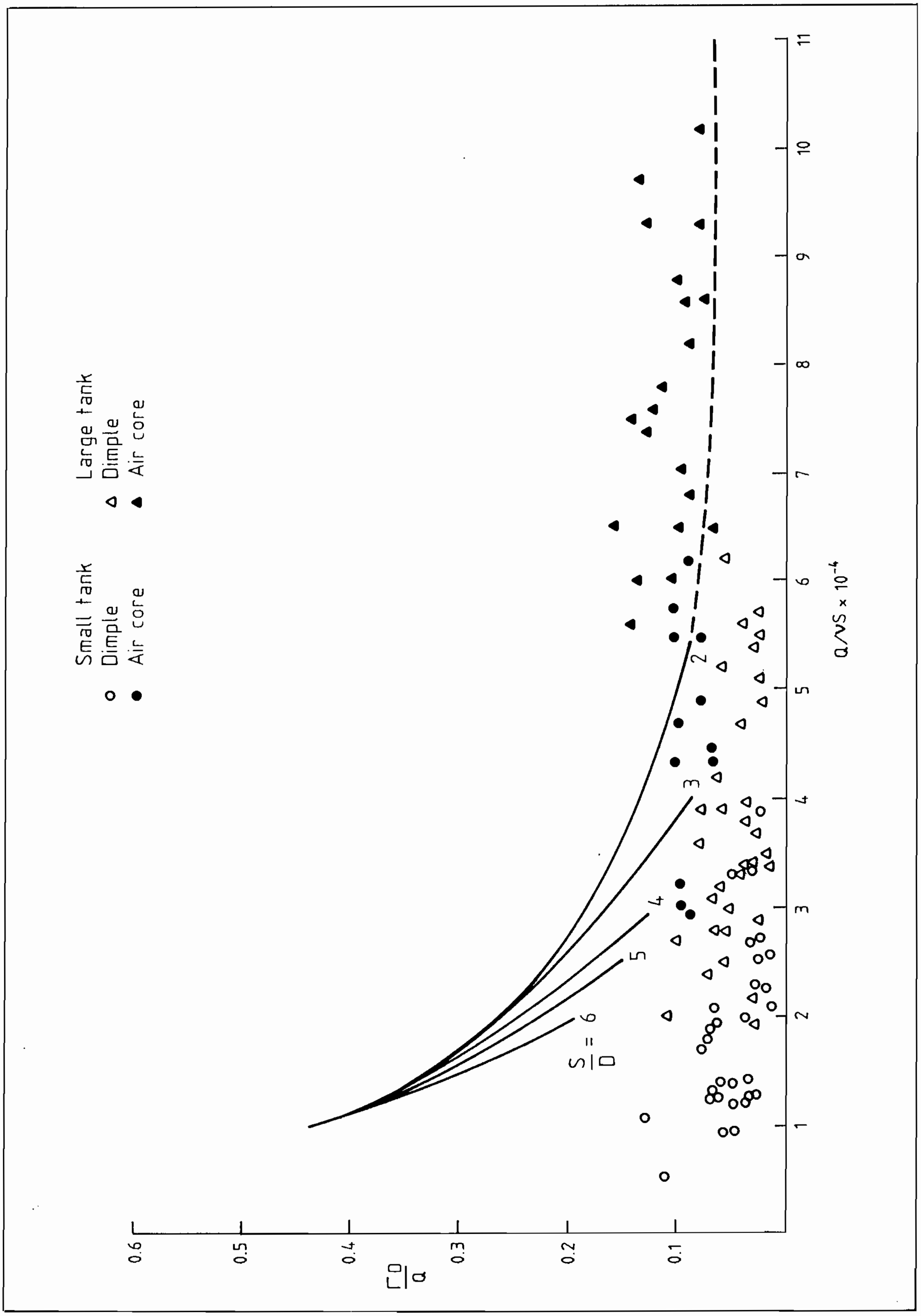
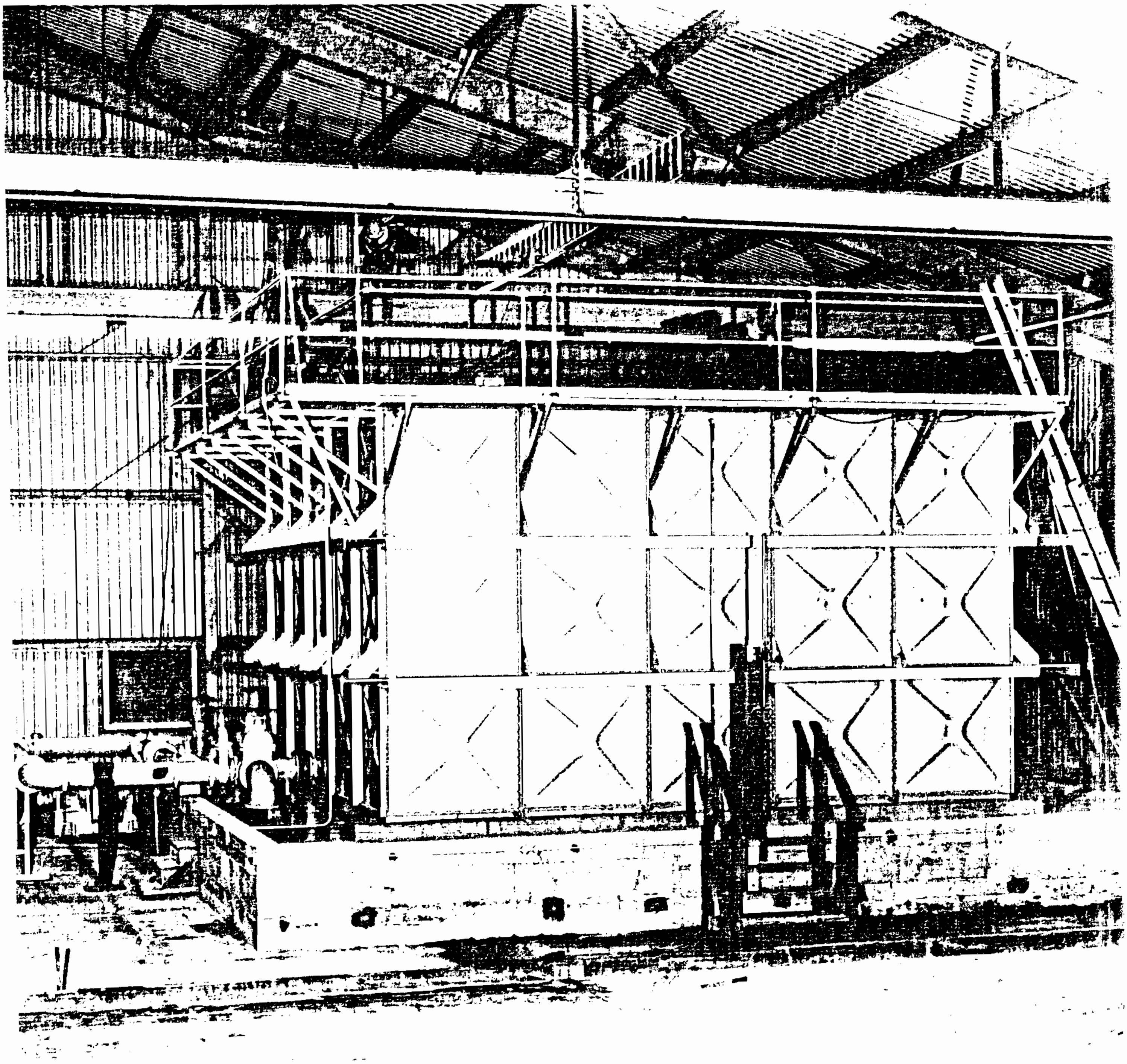


Fig 10 Threshold conditions in terms of Kolf and Reynolds numbers

PLATES



'LATE 1.   Experimental tank : external view

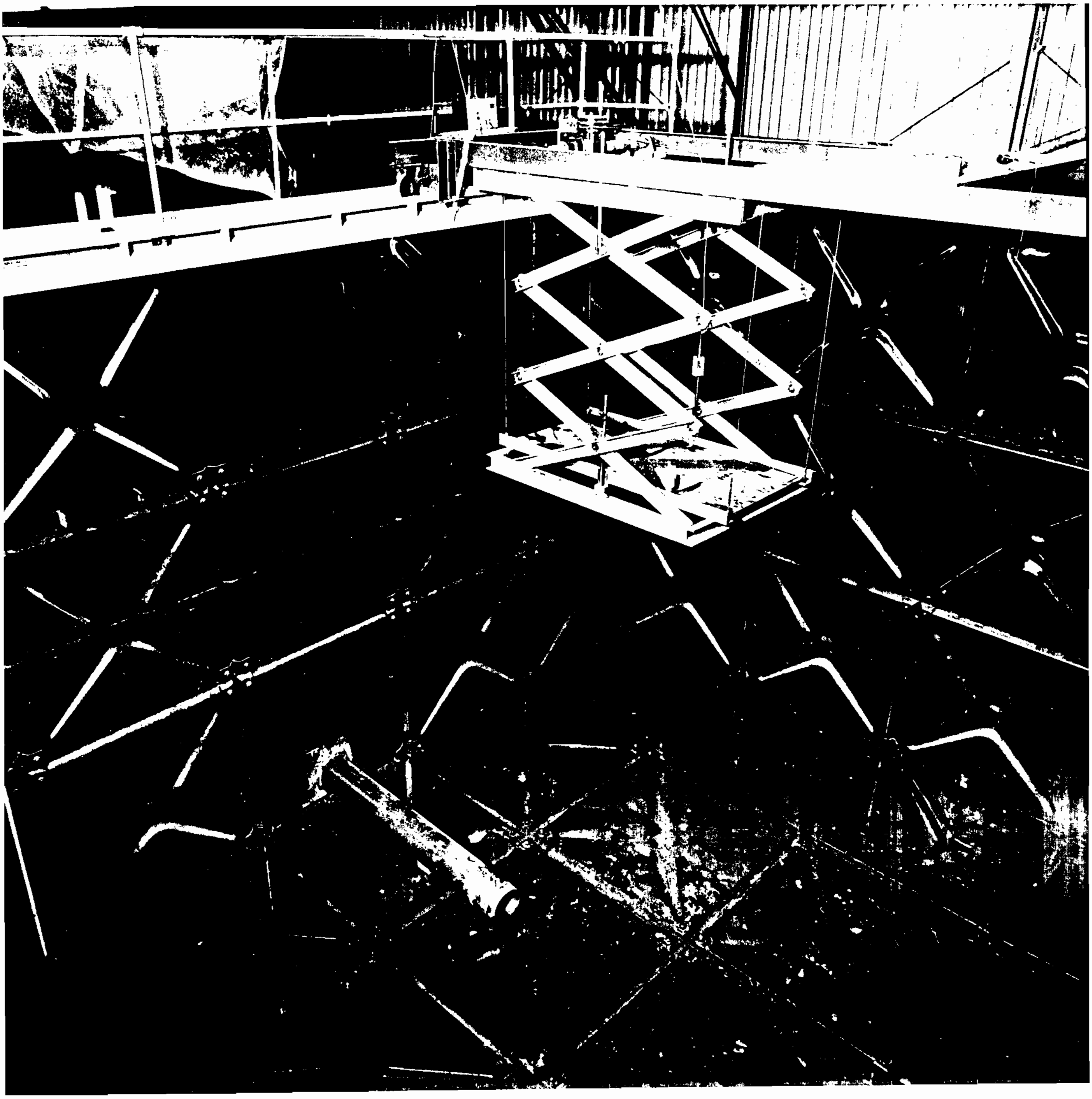
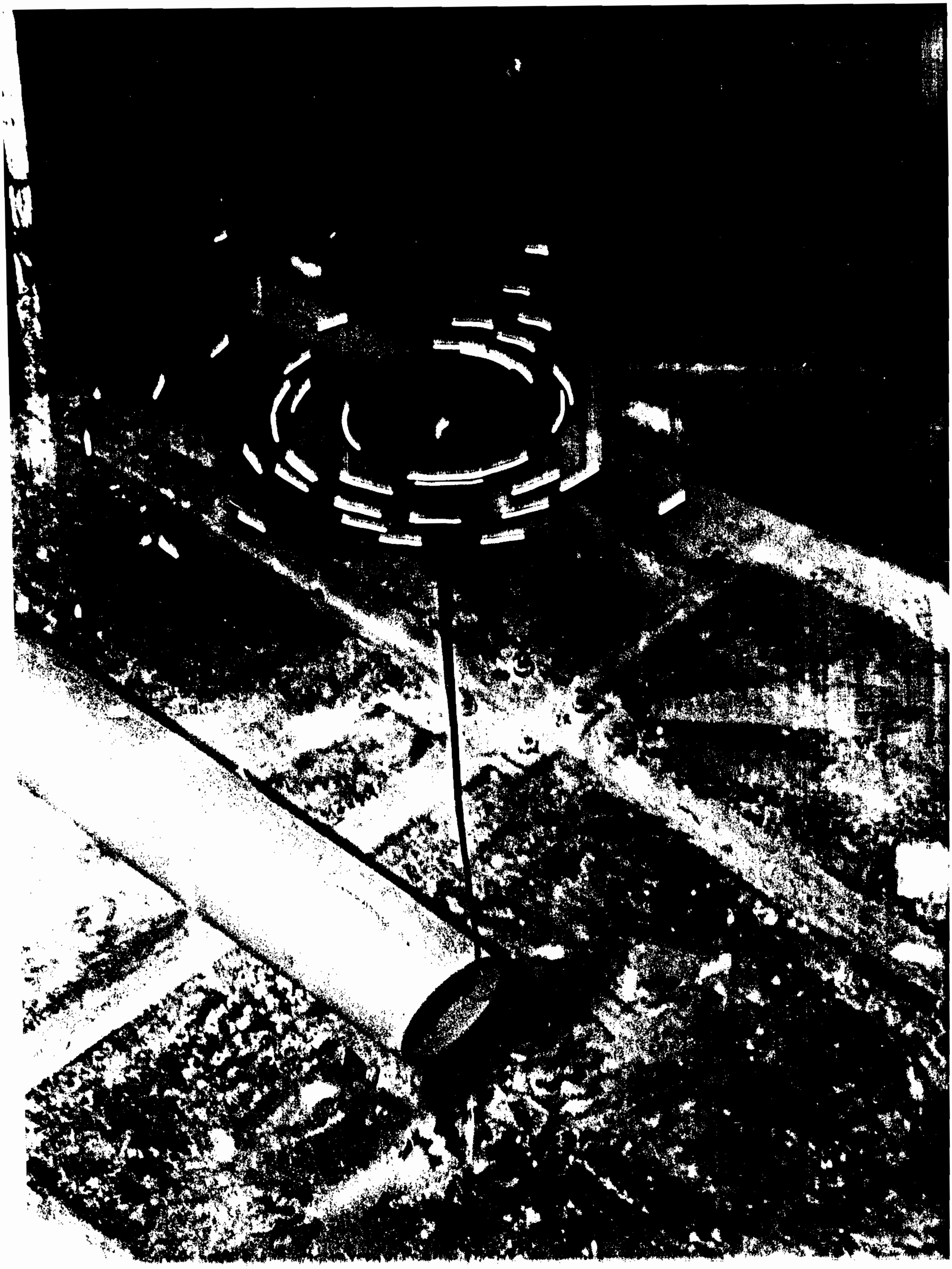


PLATE 2. Experimental tank : internal view



TE 3.   Air-core vortex in large tank

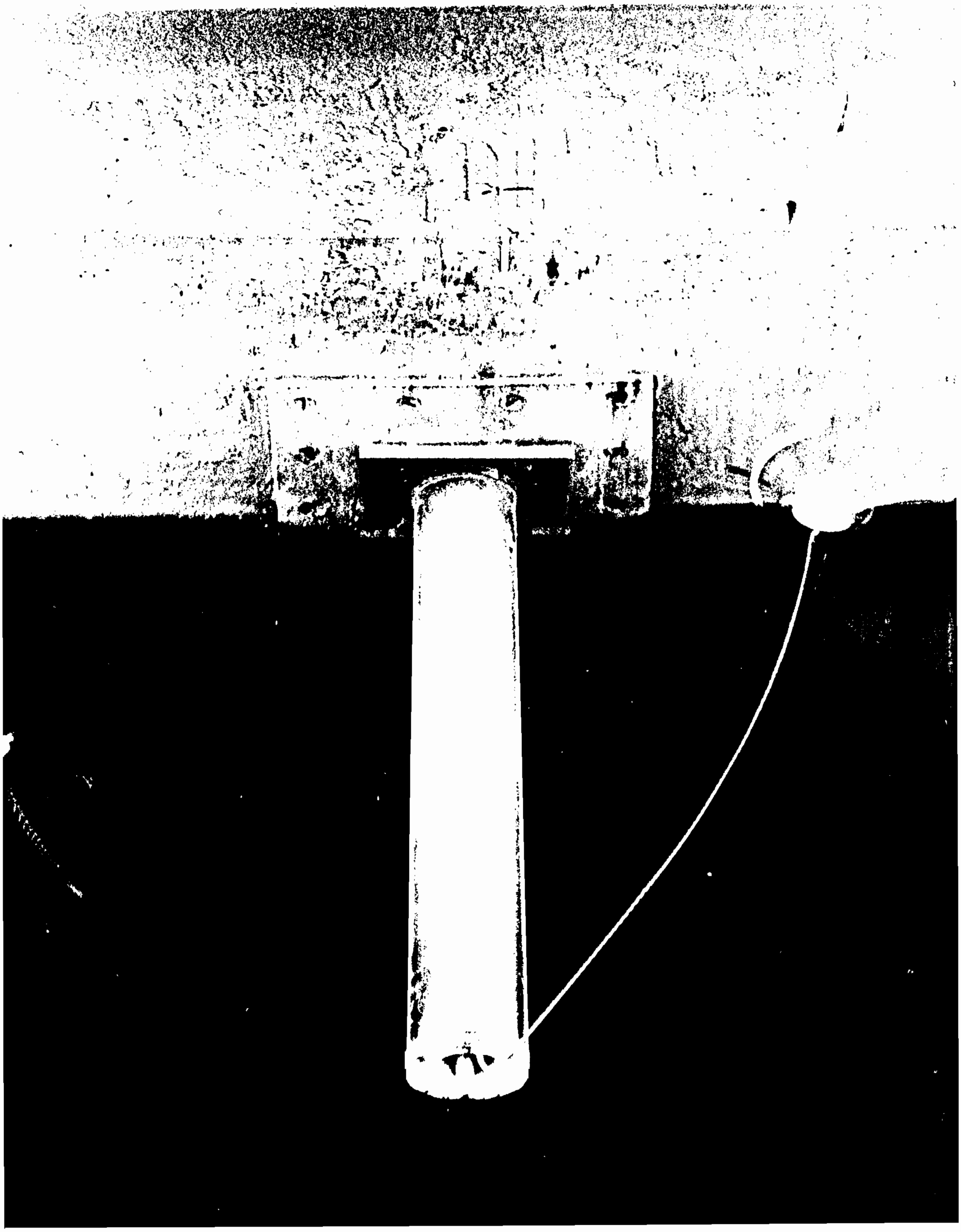


PLATE 4. Air-core vortex in small tank: from above

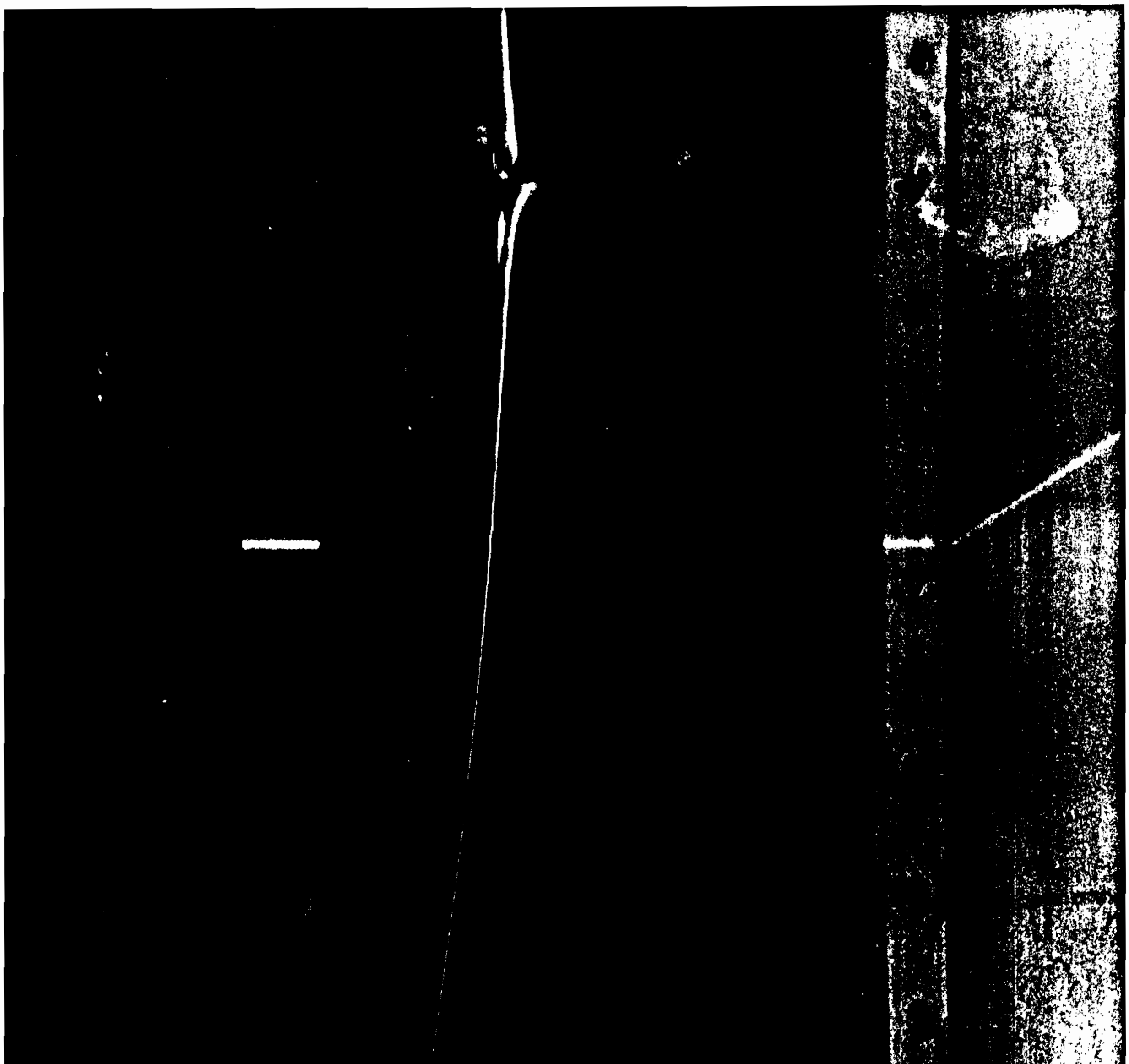


PLATE 5. Air-core vortex in small tank: from side