Hydraulics Research
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VORTEX INHIBITORS

Interim report

Report No SR 66
October 1985

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This report describes work funded by the Department of the Environment under contract PECD 7/6/29 - 204/83, Hydraulic Structures and Alluvial Processes. It is being carried out in the River Engineering Department.

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ABSTRACT

When designing a water intake it is difficult to predict whether vortices are likely to occur and how best to prevent them. Vortices are undesirable because of the adverse effect that they have on the efficiency with which the intake operates.

A research project is being carried out to compare the performance of different types of inhibitor for use with intakes in reservoirs. Initially the threshold conditions under which vortices occur at a plain intake, have been measured : tests were then carried out on different types of inhibitor to determine the extent to which the threshold conditions were changed by the inhibitor. Once the most promising types have been identified, further tests will be carried out on them, to determine their optimum geometries.

CONTENTS

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 the first stage of a research project on vortex inhibitors which is being carried out at Hydraulics Research (HR) with funding provided by the Department of the Environment. The primary aim of the study is 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. It is also planned to study the effects of scale by repeating some of the tests with models of different size. In order to carry out this research programme, HR has built a special test facility which consists of a large tank measuring 6m x 6m x 3.6m deep together with pumps, associated pipework and flow-measuring equipment. After considering previous work on vortices, this report describes the layout of the new facility, its calibration and the results of the first part of 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.

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

Γ = circulation
v = velocity component along element of circuit, of length dl
$\oint$ = 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 is equal to 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, ζz,

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

where

u = velocity in x direction
v = velocity in y direction

It can be shown that

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

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, ie 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 generated by the vorticity at the centre of the vortex.

Free vortex theory also leads to an unrealistic velocity distribution close to the centre, ie $v = \infty$ 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. That 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, eg 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) Reynolds Number (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 Anwar [5] terms as radial Reynolds numbers.

(3) Froude Number (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) Weber Number (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) Kolf Number (ratio of centrifugal to inertial forces)

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

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 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

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

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 $Q/\nu S_c$ and S_c/D for the condition of critical submergence are shown in Fig 1; the curves separate the upper region in which air-entering 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

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

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

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

Fig 2 shows the experimental curve of $\Gamma r_o/(2\pi Q)$ versus $Q/\nu S_c$ 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

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

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. The Kolf number was defined as

$$K = \frac{\Gamma S}{Q} \quad (17)$$

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

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

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

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

Equations (16) and (19) suggest that a model of a vertical intake using water at 15°C ($\nu = 1.14 \times 10^{-6}\ m^2 s$) 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

$$\left(\frac{Q}{\nu S_c}\right) > 1380 \left(\frac{D}{Q}\right)^{-0.84} \left(\frac{S_c}{D}\right)^{0.16} \tag{21}$$

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 (eg at the Kariba dam [11]) 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 [12] 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 [13] and the Orange River Project [14]. 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 [15]. 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 [16] 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 EXPERIMENTAL FACILITY

A large tank, 6m square in plan and 3.6m deep has been constructed; it has been 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 has been 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 225 mm pipe, which is connected with the inlet manifold (again 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 Fig 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 has been designed so that the flow can 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 has been 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 has been 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 has been 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 the 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 is 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 Fig 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 much of the previous research 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 75mm 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 $0.19m^3/s$ 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, 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 present series of experiments, have been based on a variety of hypotheses about the vortex-producing mechanism.

A complete list of the intake modifications tested so far 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

The inhibitors are detailed in Fig 6.

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

<u>Headwall</u>

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.

<u>Longitudinal fin</u>

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

<u>Roughening of tank floor</u>

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 and upstream. Cruciforms both within the intake and extending upstream from it, were tested.

10 EXPERIMENTAL RESULTS

The preliminary results that have been obtained from these experiments are set out in Table 1. At this stage, the comparison of the effectiveness of the different types of inhibitor has been made on the basis of the discharge at which the different distinguishing features make their first appearance.

The main conclusion to be drawn from these results is that the modifications have all had a beneficial effect: the threshold discharges at which the various characteristic features appear, are greater with the modified intake than they are with it in its unmodified state. However some modifications are more effective than others. The large headwalls require a significant increase in the threshold discharge in order to generate the various characteristic features: the major disadvantage of this type of inhibitor is that it is a massive structure in its own right and on these grounds alone is probably not a very practicable form of solution.

The inhibitor that is the best combination of effectiveness with practicability is the extended fin with height equal to 2 x intake diameter. Further study of this type of inhibitor is required in order to determine the optimum geometry.

11 FUTURE EXPERIMENTAL PROGRAMME

Various other types of inhibitor remain to be tested. These include:

(a) a square intake having the same cross-sectional area as the present circular one

(b) an enlarged entrance to the present circular intake

(c) a vertical shaft located a short distance downstream from the face of the present circular intake

(d) an inclined wall between the face of the present intake and the rear wall of the tank

(e) a floating raft.

One of the major factors in determining the rate at which the experiments can be done, is the time required for flow conditions to be established in the experimental tank; although the volumetric rates of flow are appreciable in laboratory terms, there is a large volume of water in the tank, so that flow velocities are still quite low. In order to speed up the experiments, a small tank, which is a scaled down version of the main experimental tank, is being modified for use in the testing of the remaining inhibitors.

When the most promising inhibitors have been selected on the basis of the initial tests, carried out in either the main or the small experimental tanks, further experiments to determine the optimum geometry will be carried out in the small tank. Final experiments to confirm the performance will then be carried out in the main tank.

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TABLES

TABLE 1

Vortex type	Water depth: m	THRESHOLD DISCHARGES : m^3/s												
		Original	Headwall 0.61m	Headwall 1.22m	Headwall 1.83m	Headwall 2.44m	Roughness	Fin; height 2D	Extended fin; 2D	Fin; height D	Extended fin; D	Cruciform; vertical	Cruciform; extended	Diagonal cruciform
Dimple	1.2	0.022	0.031	-	0.030	0.043	0.025	0.038	0.045	0.039	0.037	0.051	0.030	0.043
	1.8	-	0.080	0.079	0.075	0.100	0.048	>0.205	0.106	0.052	0.061	0.090	0.101	0.107
	2.48	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
Material drawn down	1.2	0.053	0.057	-	0.063	0.168	0.043	0.092	0.125	0.065	0.076	0.058	0.061	0.059
	1.8	0.076	0.115	0.154	0.109	0.127	0.098	>0.205	>0.205	0.100	0.105	0.111	0.109	0.115
	2.48	0.182	0.165	0.154	>0.205	>0.205	>0.205	>0.205	>0.205	0.121	0.145	0.172	0.168	0.136
Air core	1.2	-	0.115	>0.205	0.162	>0.205	0.067	0.136	>0.205	0.083	0.085	0.065	0.079	0.077
	1.8	0.093	0.176	>0.205	>0.205	>0.205	0.130	>0.205	>0.205	>0.205	0.157	0.155	0.177	0.139
	2.48	0.193	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 indicates that the particular vortex type could not be produced for that combination

FIGURES

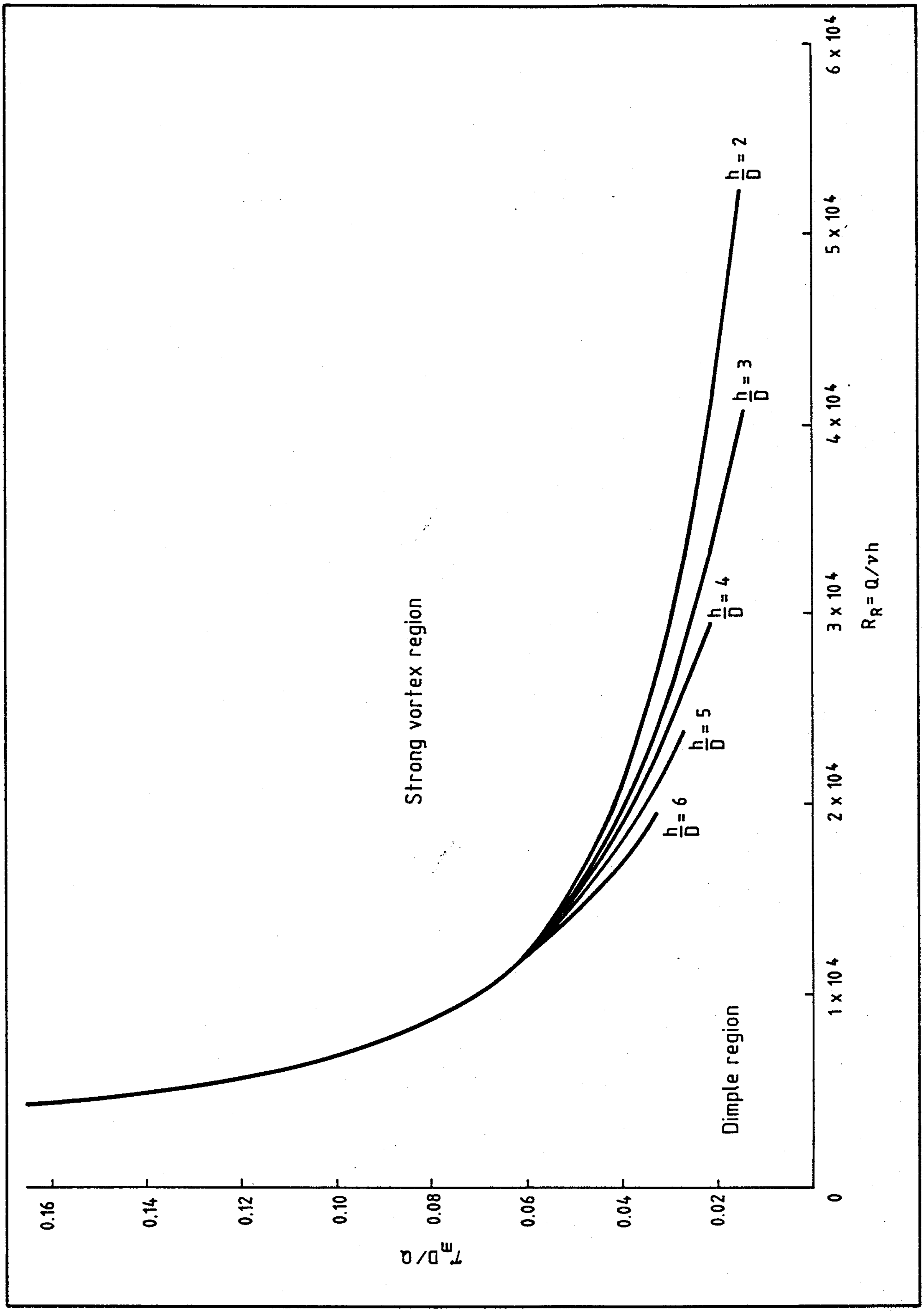


Fig. 1 Circulation parameter as a function of radial Reynolds number and submergence

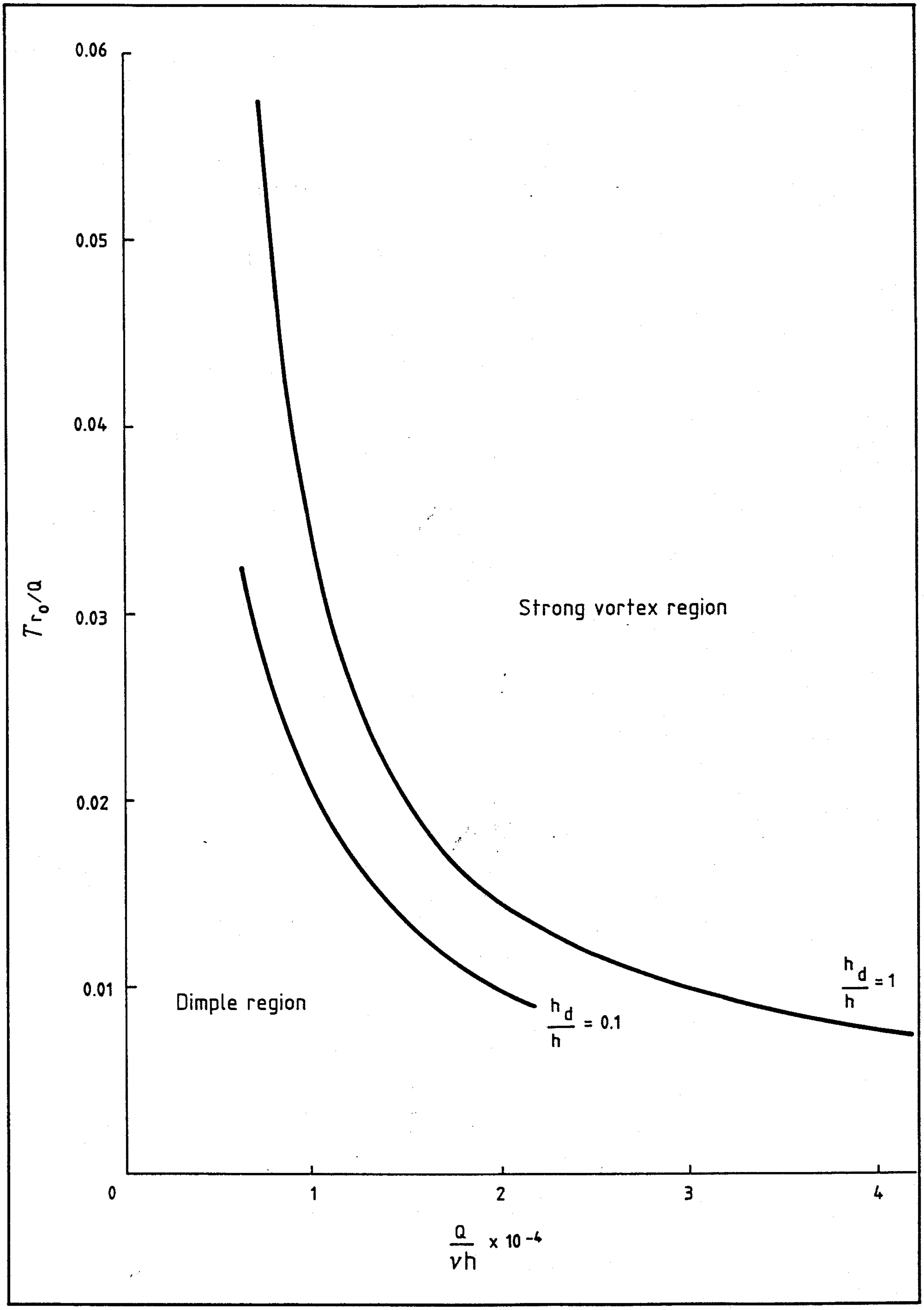


Fig. 2 Limiting conditions for different vortex types

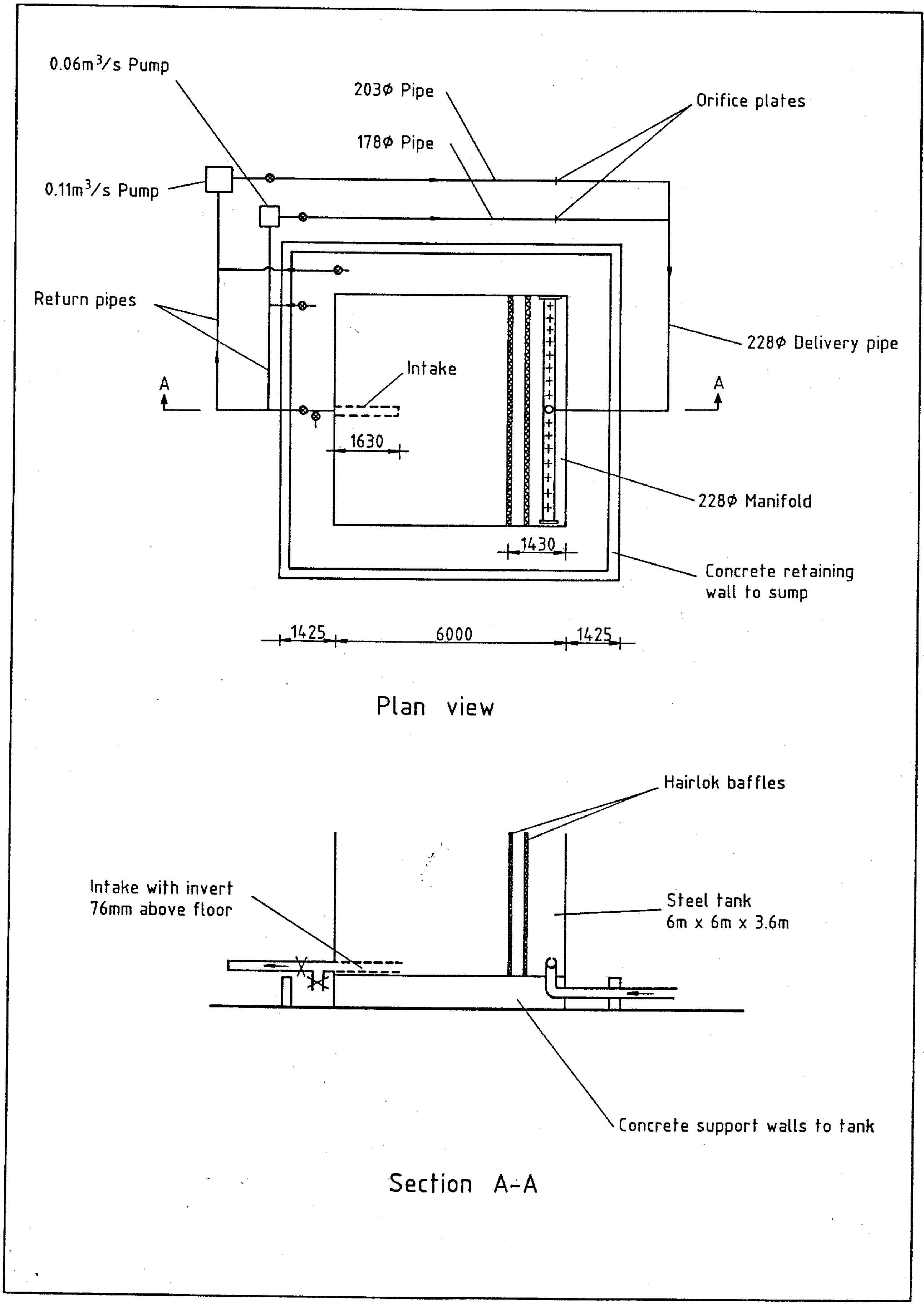


Fig. 3 General layout of experimental tank

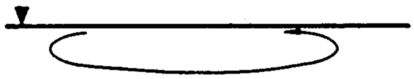
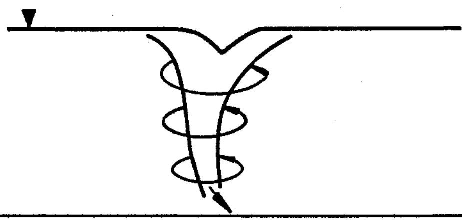
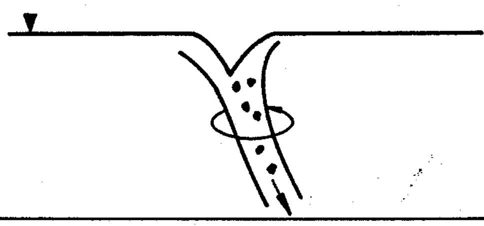
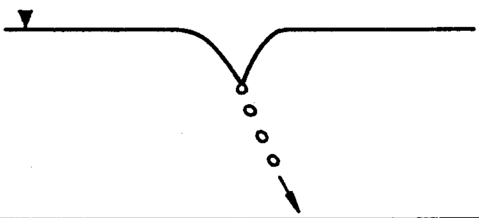
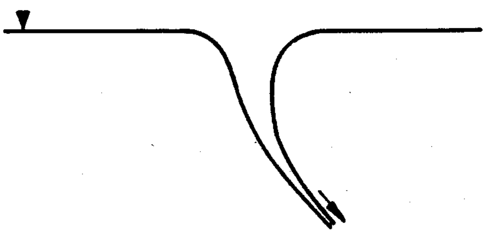
Vortex strength scale		
1		Surface rotation
2		Surface depression with minor dimples. Rotating column of water without significant draw to intake.
3		Surface dimple. Rapidly rotating narrow water core with draw to intake.
4		Draw of water and floating trash to intake.
5		Draw of air bubbles to intake.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

Fig. 4 Vortex strength classification

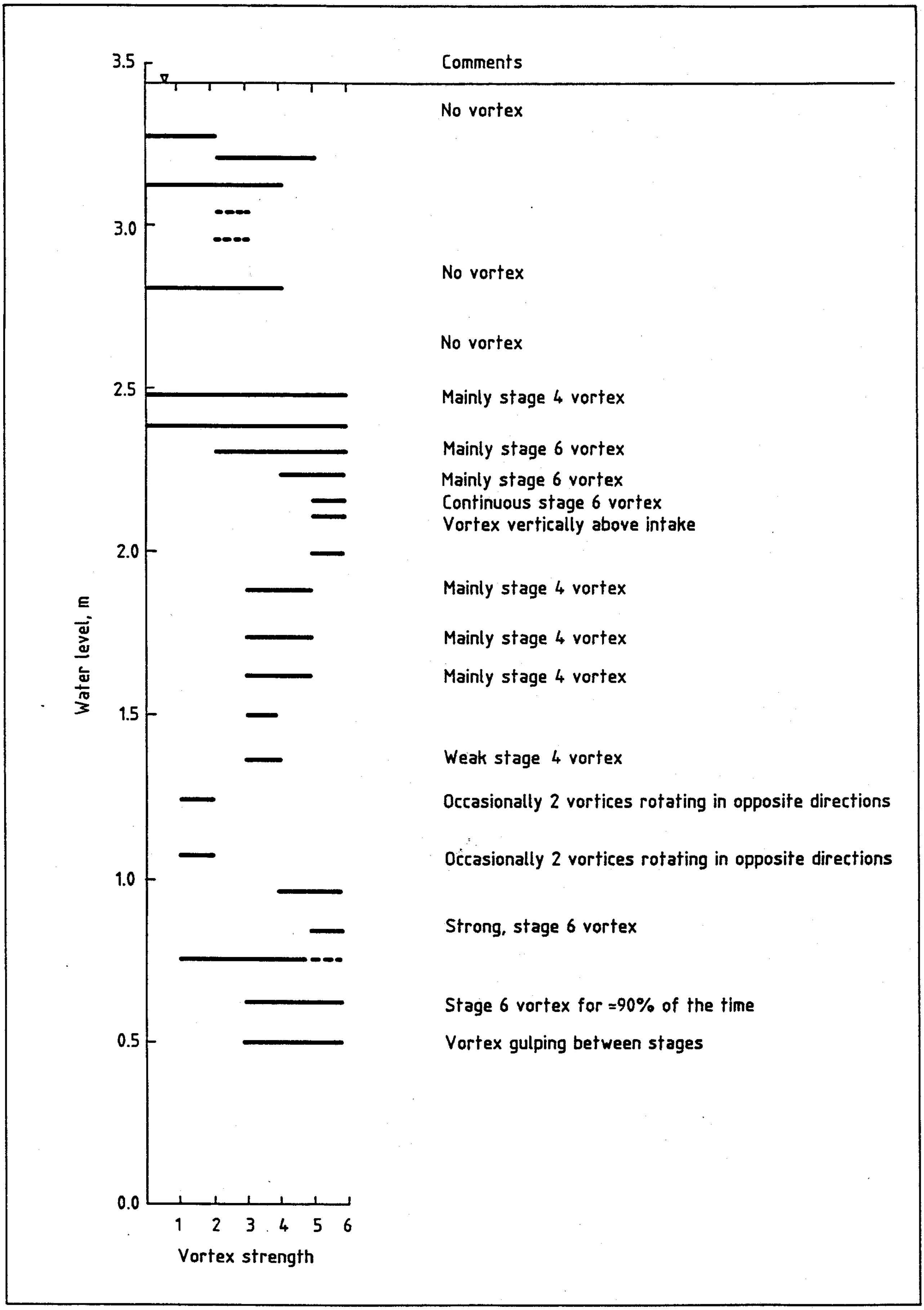
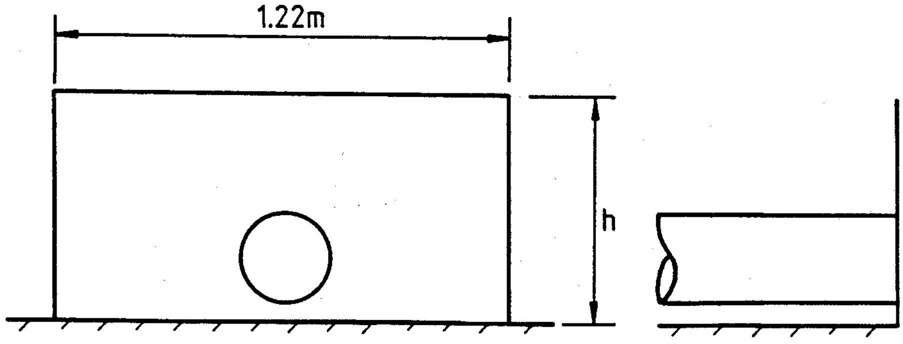
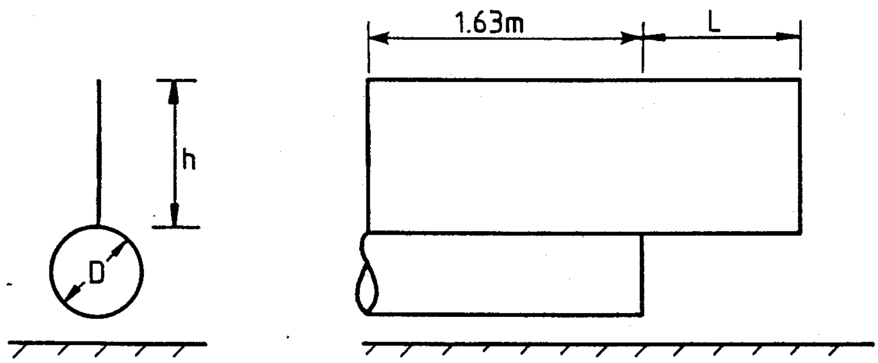


Fig. 5 Variation of vortex strength with water level : projecting intake



Headwall

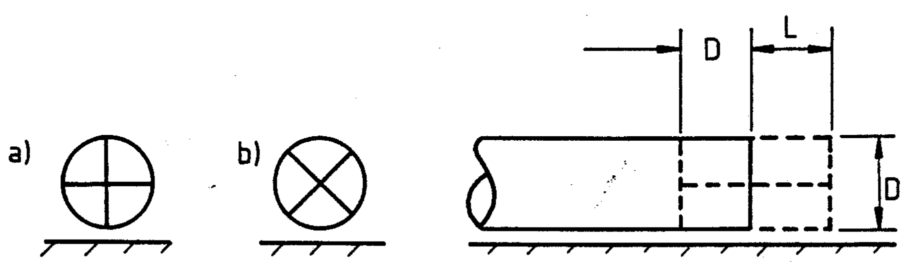
Tests carried out with h = 0.61, 1.22, 1.83, and 2.44m respectively.



Fin

Tests carried out for

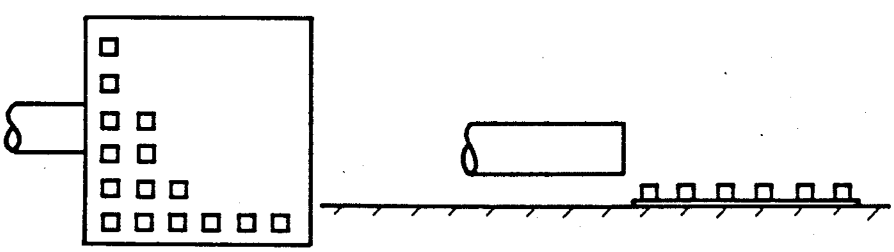
h	L
D	0
D	D
2D	0
2D	2D



Cruciform

Type a) with L = 0,D

Type b) with L = D

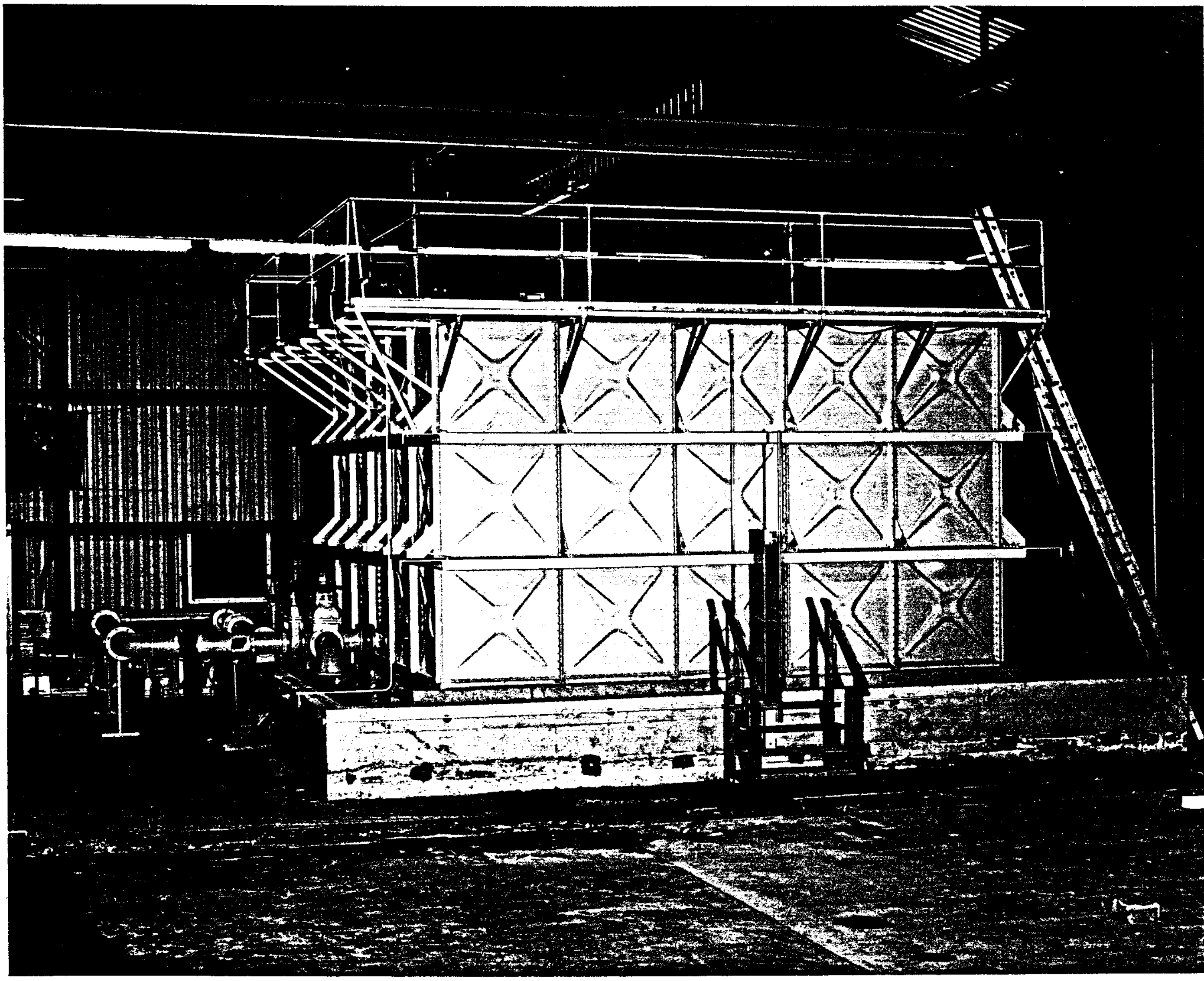


Roughness

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

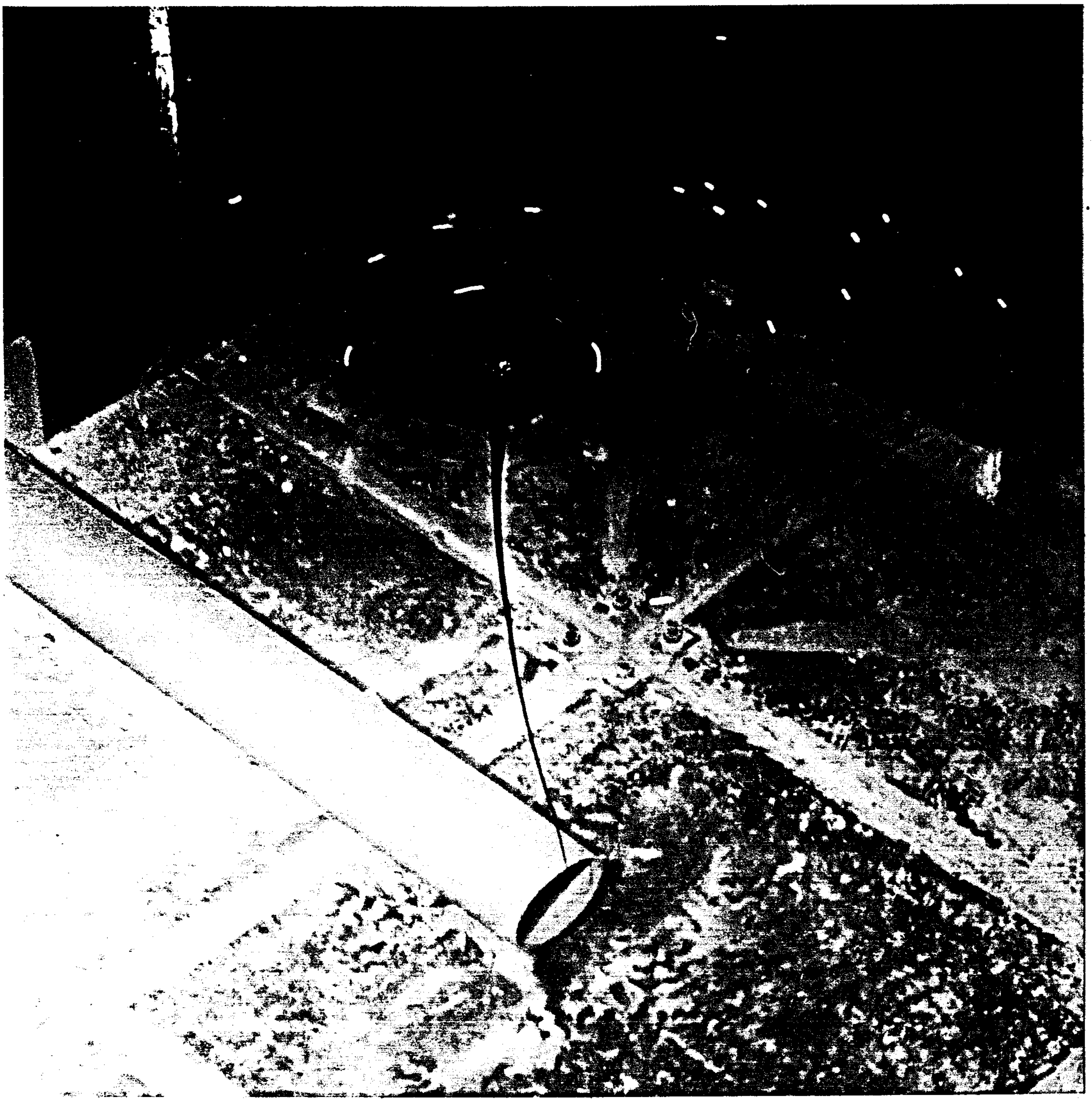
Fig. 6 Types of inhibitor

PLATES



1 Experimental Tank : External View

2 Experimental Tank : Internal View



3 Air-core Vortex