ACRES

January 22, 1986
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Mr. Bruce Bennett
NATIONAL HYDRO CORPORATION
77 Franklin Street
Boston, MA 02110

Dear Mr. Bennet::

Pembroke Hydroelectric Project
<u>Intake, Vortex Suppression Device</u>

As requested, we attach information on a vortex suppressant raft. The design of the vortex raft attached was model tested for a similar project and found to perform satisfactorily. As you can see, it is made up of 8" wide by 16" deep timber on 2'2" centers. I am advised by our Hydraulic Department that the lattice spacing is a function of the vortex fize and that it should be smaller than the vortex diameter. Additionally, the raft must be sufficiently large so that it is not drawn down into the flow.

We suggest that when the intake is tested at minimum headwater level, the diameter of the vortex, if any, be measures so that the correct lattice spacing can be determined.

I am also enclosing some literature references which you may wish to review.

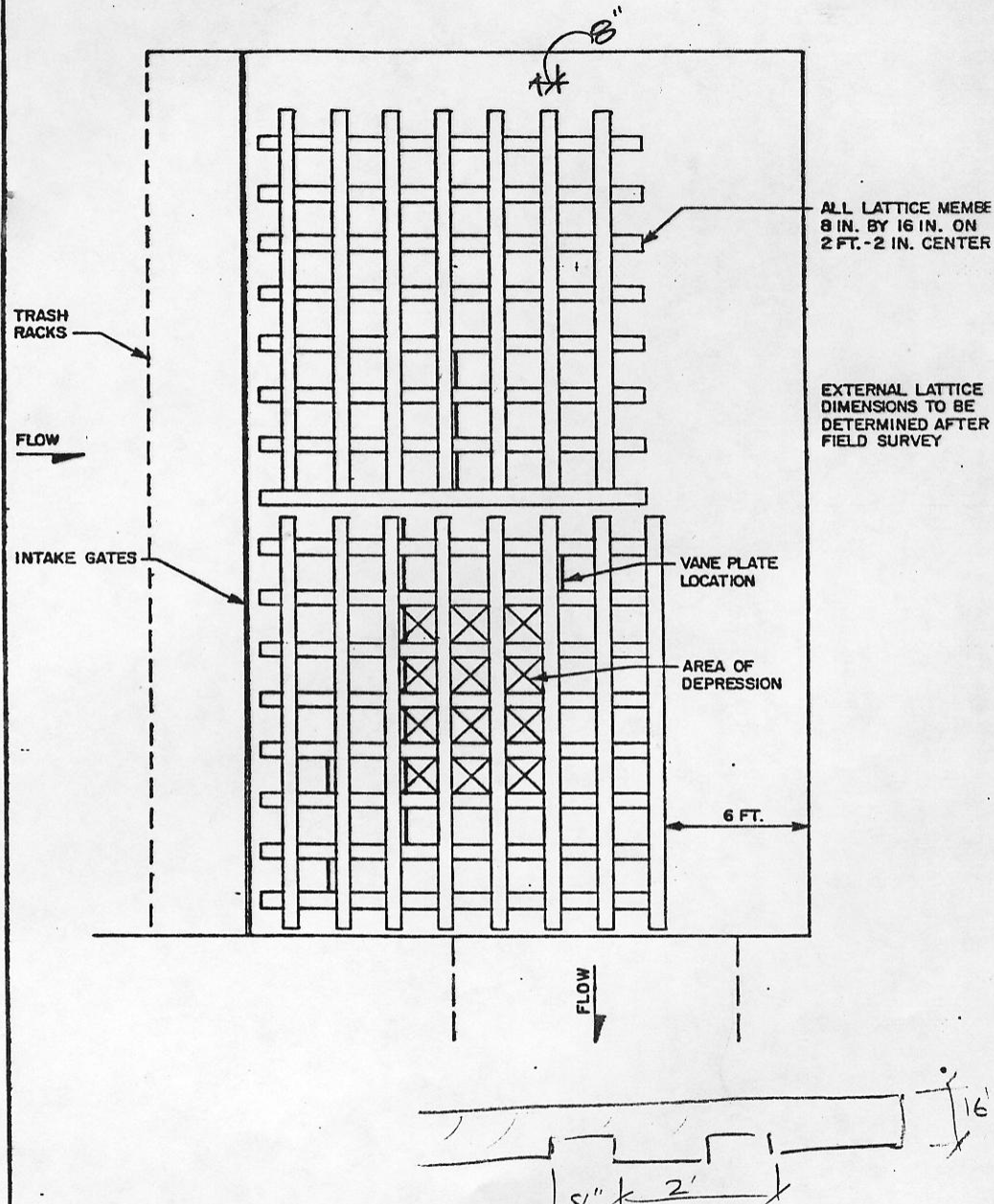
Very truly yours,

Olaf M. Erickson, P.E.
Project Manager

OME/jk
Attach.

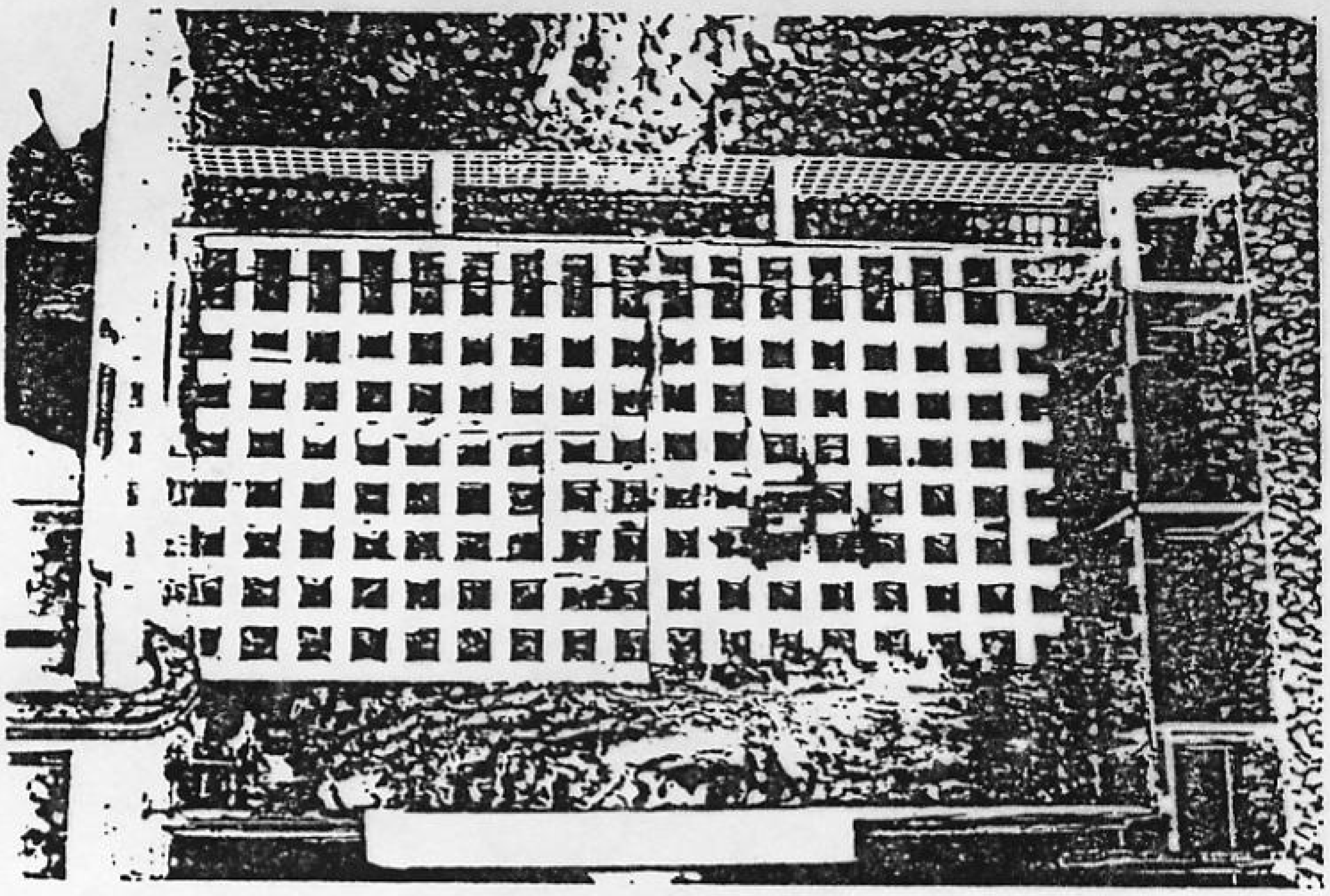
CC - Tom H. @ Bancroft C.B. 2/3/86

ACRES INTERNATIONAL CORPORATION
Engineers, Architects and Planners
Suite 1000, Liberty Building, 424 Main Street,
Buffalo, New York 14202-3592
Telephone 716-853-7525 Telex 91-6423

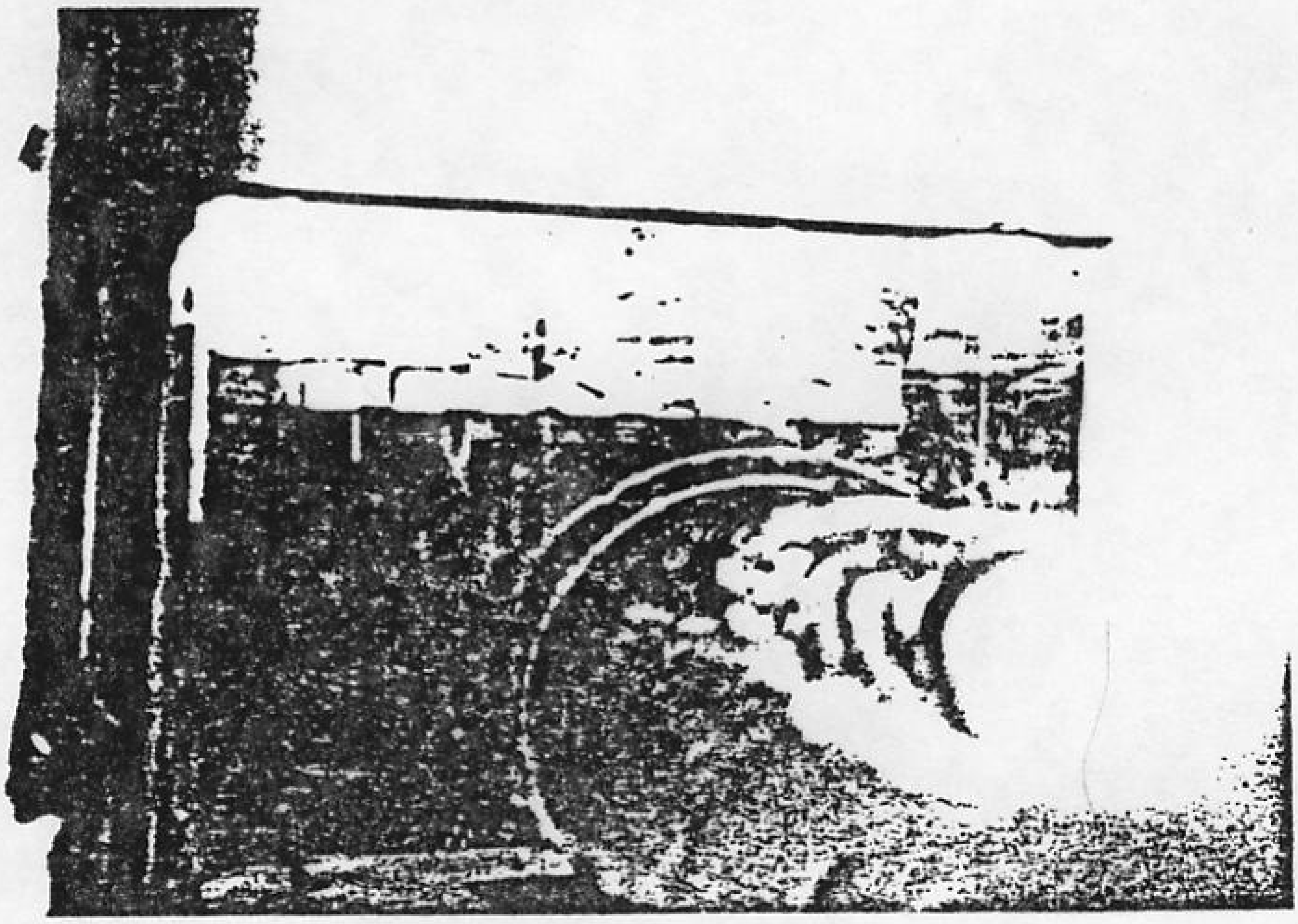


REFINED TIMBER LATTICE

FIGURE 8



Photograph 9 (a) - Plan View - Refined Timber Lattice



Photograph 9 (b) - End View - Refined Timber Lattice

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Brian French

Vortices at intakes

By J. L. Gordon*

This article describes the development of design criteria to avoid vortices at low-head intakes, based on a study of 29 existing hydroelectric intakes

FOR A CONVENTIONAL hydroelectric intake, with a deck slab set above water level, the cost of the intake structure increases with increasing depth of gate sill below water level. For maximum economy the gate sill should be set as high as possible. However, with gate sills at a shallow depth, there is a danger of vortices forming, which may entrain air, thus reducing the efficiency of the turbine. The problem then becomes one of establishing the gate sill at as high a level as possible for economy, but below the level at which vortices are produced for hydraulic efficiency.

There are very few published reports on experiences with vortices at intakes, and in particular there appear to be few data published on just what can be regarded as the submergence required to avoid vortices. Model studies can be undertaken, but on a small intake the cost of a model study may exceed the cost of the intake structure. Several model studies have been undertaken by Anwar[1] and Denny[2], however there is the suspicion that a considerable scale effect may be involved, since viscosity and the forces governing entrainment of air are important, as acknowledged by Lawton[3].

The experience gained from a study of the flow at intakes which have been designed by Montreal Engineering Co Ltd, of Canada, in the past 20 years is included in this article. The study was prompted by the observation of a vortex at low reservoir drawdown on one of the intakes. Of the 29 intakes studied, four were found to have vortices at low reservoir levels. All intakes studied have the same general configuration as shown in Fig. 1, and their characteristics are all within the following limits:

	Lowest	Highest
Velocity at gate V	3·41ft/s	22·2ft/s
Submergence s	4·5ft	67·0ft
Gate height d	4·2ft	26·0ft
Gate width w	4·2ft	22·0ft
d/w ratio	0·9	1·5

The factors which appear to affect the formation of a vortex are: the geometry of the approach flow to the intake; the velocity at the intake; the size of the intake and the submergence.

It is obvious that an intake with the flow approaching from the side (as shown in Fig. 2) will be more prone to vortices than one with a symmetrical approach. However this effect is difficult to measure, particularly since the geometry of the intake approach channel is probably unique to each intake. Accordingly, it was decided to concentrate on investigating the effects of velocity, intake size, and submergence on vortex formation.

In order to derive an empirical equation for submergence, it was assumed that the submergence S was a function of a velocity and a dimension as shown by the following equation:

$$S = C\,V^n\,d^m \qquad .. \quad (1)$$

where C is a coefficient.

For simplicity it was decided to measure velocity at the gate and use the height of the gate as the dimension function d. The submergence could be measured either from the top of the gate or from the gate centreline. However, after several trials using various values for the exponents n and m it became apparent that a better relationship could be obtained when submergence was measured from the top of the gate as shown in Fig. 1. The trial and error procedure indicated that a reasonable relationship could be obtained with the exponent $n=1$ and $m=\frac{1}{2}$ which produces the equation:

$$S = C\,V\,(d)^{\frac{1}{2}} \qquad .. \quad (2)$$

and the chart shown on Fig. 3.

The effect of the direction of the approach flow could not be clearly evaluated in this brief study. However, until more data become available, we intend to design

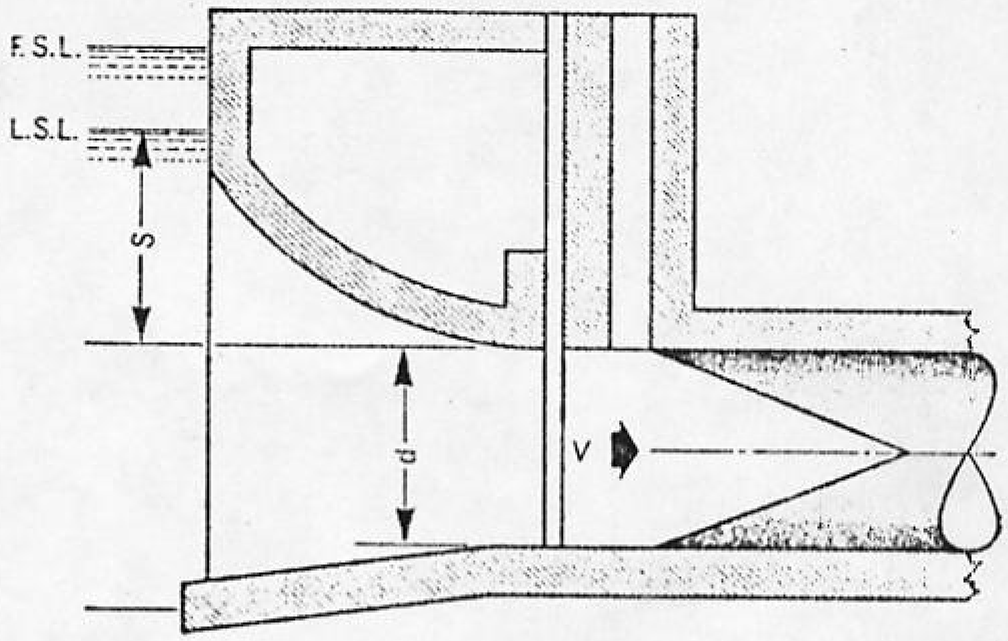

Fig. 1. General configuration of an intake

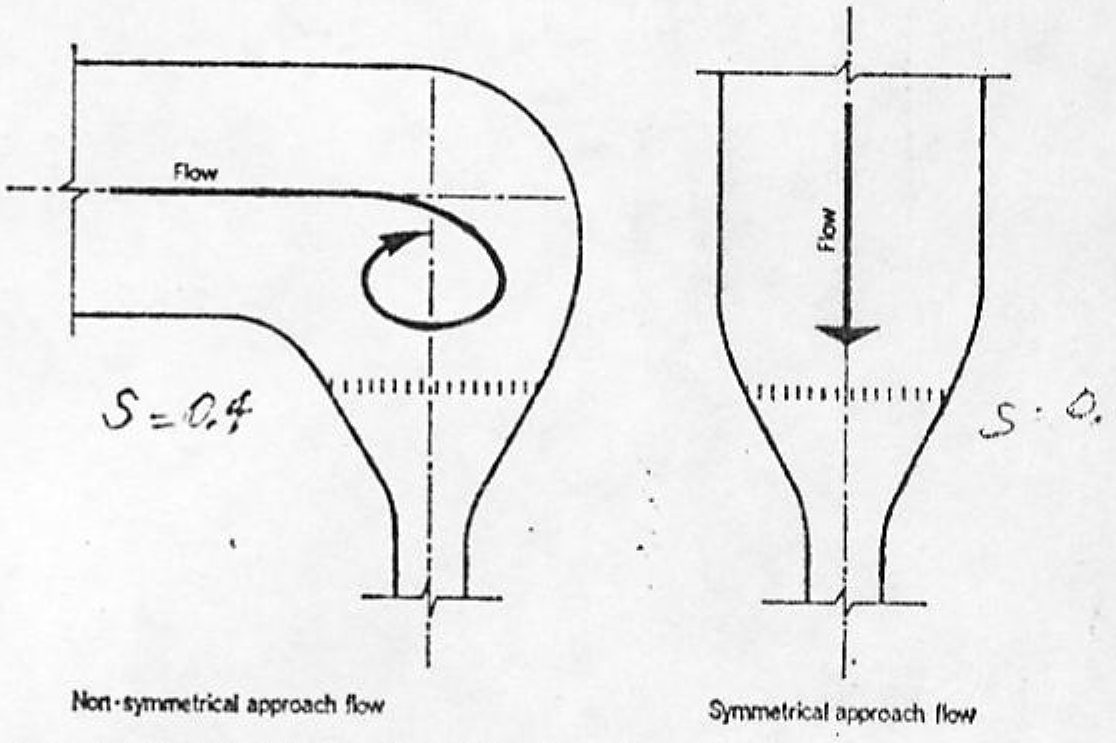

Fig. 2. Intake with flow approaching from the side

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* Assistant Manager, Hydro Division, Montreal Engineering Co. Ltd., Place Bonaventure, Montreal 11A, P.Q., Canada.

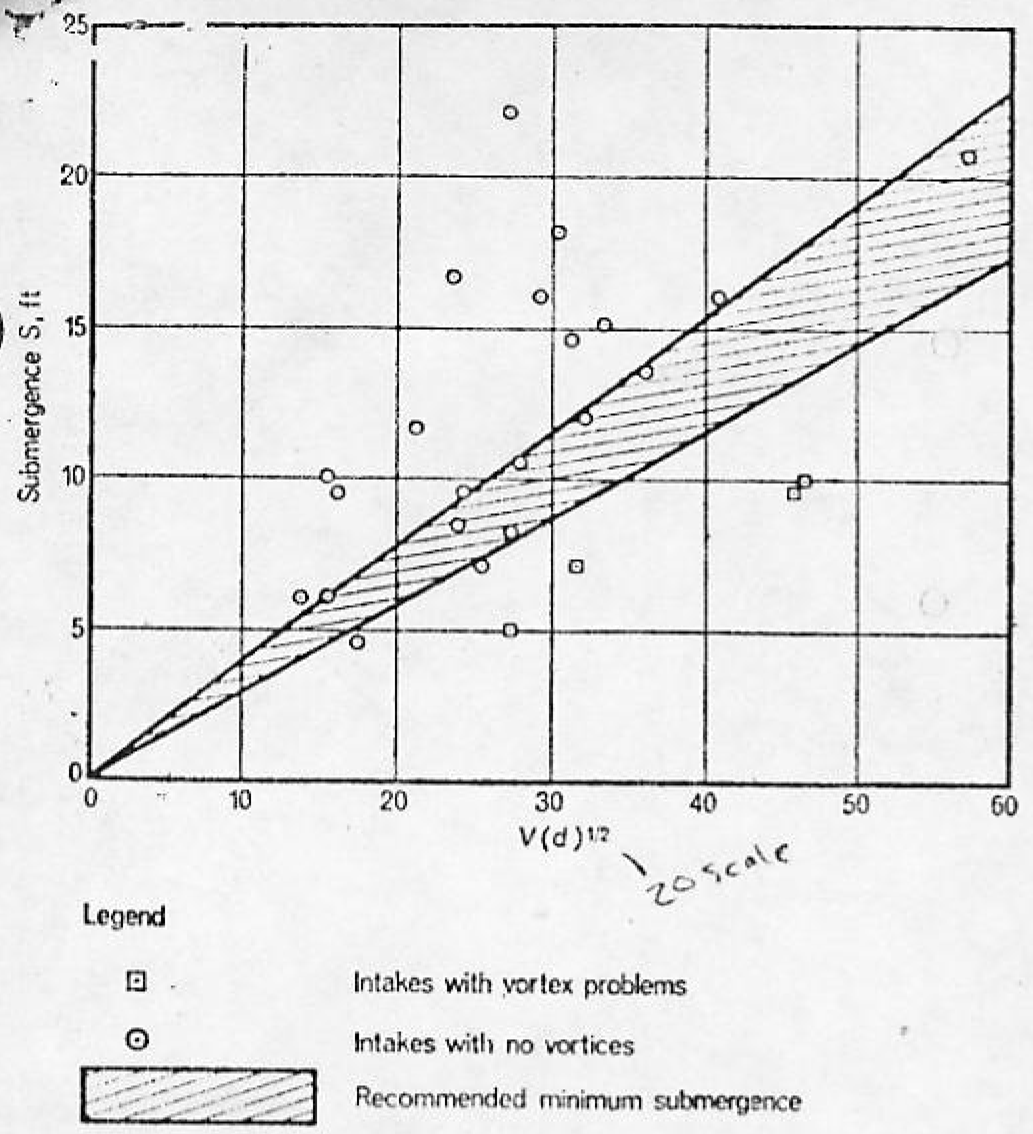

Fig. 3. Minimum submergence limits for intakes with both symmetrical- and lateral-approach flows

intakes which have a symmetrical approach flow with a submergence of at least:

$$S=0{\cdot}3\ V\,(d)^{\frac{1}{2}} \qquad .. \quad (3)$$

which corresponds with the lower limit of the shaded area on Fig. 3, and for intakes with a lateral approach flow the minimum submergence will be increased to:

$$S=0{\cdot}4\ V\,(d)^{\frac{1}{2}} \qquad .. \quad (4)$$

which corresponds with the upper limit of the shaded area on Fig. 3.

Some confirmation of the foregoing submergence criteria can be obtained from Lennart[4], who gives data on several intakes in Sweden which exhibit vortices. At the Atorp power plant, Lennart reports that "a rather strong surging vortex arose. This sucked down trash towards the racks." The submergence of the intake at Atorp corresponds to approximately $S=0{\cdot}1\ V\,(d)^{\frac{1}{2}}$ with the unit at full load. Lennart further reports that "at lower discharges the eddy zone decreased correspondingly and at about 15m³/s it became imperceptible". At this lower flow the effective submergence increases to $S=0{\cdot}3\ V\,(d)^{\frac{1}{2}}$.

For the Hammarforsen intake, also reported by Lennart, strong vortices were evident at a submergence equivalent to $S=0{\cdot}28\ V\,(d)^{\frac{1}{2}}$, and the flow approached the intake at an angle of at least 30-45° from the perpendicular to the front of the intake. It would be interesting to know if these vortices disappeared when the flow was reduced, increasing the effective submergence to $S=0{\cdot}4\ V\,(d)^{\frac{1}{2}}$.

An idea of the scale effect can be obtained by comparing the submergence criteria with the results obtained by Denny[2] from model experiments. Fig. 4 shows the intakes plotted on the chart developed by Denny (Fig. 13a in Ref. 2). All the intakes, with one exception, plot in the region where vortices could be expected from model studies, whereas experience indicates that only four have encountered troublesome vortices. A partial explanation may be in the definition of "vortex problems". For hydro-intakes the development of small surface riffles or swirls is of no concern, provided the swirls do not develop into vortices which draw air into the pipeline. Once air is entrained vortices become a problem.

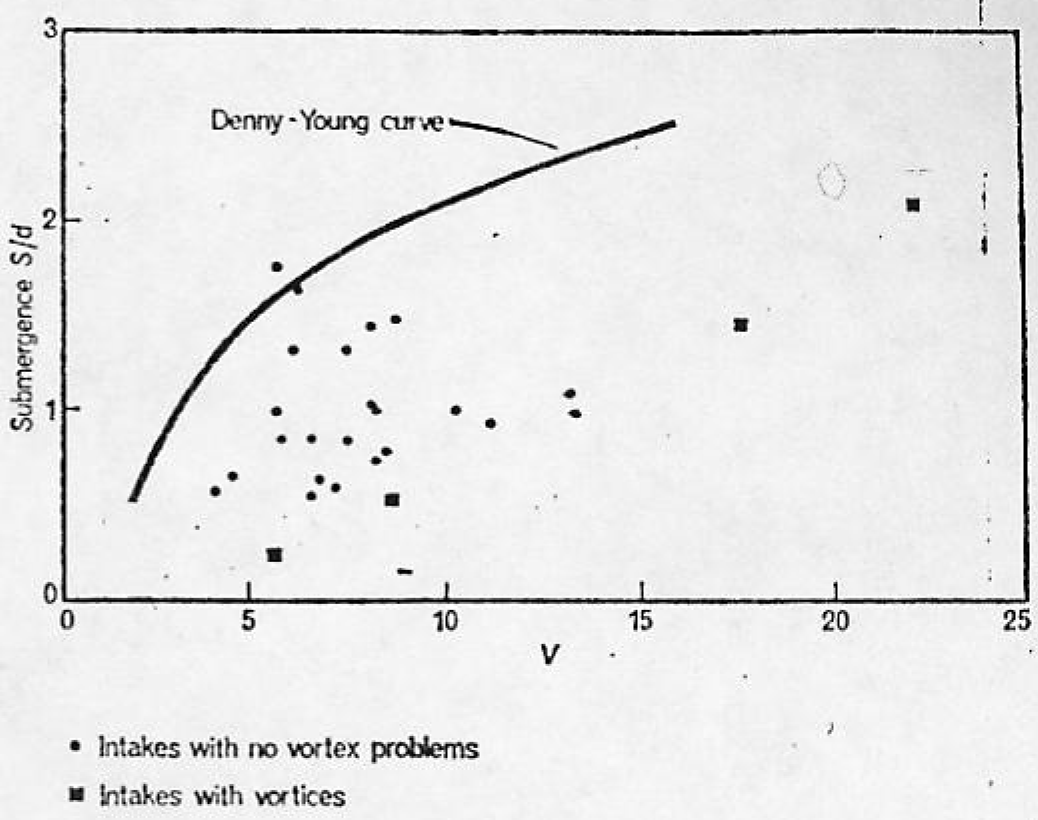

Fig. 4. Intakes plotted on a chart developed by Denny

In conclusion, it is apparent that further research is required into the factors which affect vortex formation. Due to the scale effect, this could best be undertaken on several existing hydro intakes where the flow and the reservoir low supply level can be varied as necessary.

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THE PREVENTION OF VORTICES AND SWIRL AT INTAKES

by D. F. DENNY and G. A. J. YOUNG

British Hydromechanics Research Association, Harlow, Essex, England

Summary. Air-entraining vortices and swirl at intakes are shown to be due to the presence of persistent rotational flow in the body of water approaching the intake. Experimental results showing the effect of depth of water, velocity of water through the intake, shape of intake and strength of the rotational flow are presented and discussed. These results indicate ways in which vortex and swirl problems can be avoided by good initial design, and remedies which can be applied when they are found in existing installations.

Experiments with models of installations are described and in some cases comparison between model and prototype over a limited range has been made. Within this limited experience there is evidence that air-entraining vortices only occur under similar submergence conditions when prototype velocities are used.

Sommaire. Il est montré que les vortex entraînant de l'air se produisant devant les prises d'eau et l'écoulement spiral à travers les prises d'eau sont dûs à la présence d'un courant rotationnel persistant dans la masse liquide approchant la prise d'eau.

Des résultats experimentaux sont présentés et discutés; ils montrent l'effet de la profondeur d'eau, de la vitesse de l'eau à travers la prise, de la forme de la prise et de la puissance du courant rotationnel. Ces résultats indiquent la façon dont les problèmes de vortex et de l'écoulement spiral peuvent être évités par un bon projet initial et les remedes à appliquer quand on a à les resoudre dans des ouvrages existants.

Des expériences sur des modèles d'ouvrages sont décrites et dans quelques cas on a pu comparer, dans un domaine limité, le modèle et le prototype. Dans le cadre de cette expérience limitée, il apparaît que les vortex entraînant de l'air ne se produisent, dans des conditions de submersion semblables, que lorsque les vitesses du prototype sont utilisées.

1. Introduction

The function of an intake is to direct water from a sump, channel or reservoir into the pipe-line or tunnel. At first sight the only hydraulic problems that could arise would be in connection either with filtration or with loss of head. However it has become apparent in recent years that the siting of the intake relative to the direction and boundaries of the approaching flow may be very important if an additional flow problem is not to be encountered. This is the setting-up of persistent rotational flow in the body of water approaching the intake, leading to air-entraining vortices, or «whirlpools».

The air carried into the intake in this manner may easily reach 5 % of the water-flow, and can thus have disastrous effects on the efficiency of hydraulic machinery, apart from the danger of vibration or corrosion damage to pipes and tunnels. For instance 1 % of air is known to be capable of reducing the efficiency of a centrifugal pump by as much as 15 %.

The second part of the problem arises because the rotation of the oncoming water may not be destroyed before passing through the intake, but may re-appear as swirling flow in the pipe or tunnel. The effect of swirling flow on the performance of hydraulic machinery is uncertain but there are many cases where serious drop in pump efficiency or overloading of driving motors has been attributed to swirl. Axial-flow machines would appear to be particularly susceptible.

The origin of the problem of persistent rotational flow lies in the relation between the position of the intake and the direction of the approaching flow. If in the oncoming flow there is, for any reason, a resultant angular momentum about a vertical axis at the intake, then rotational flow will result and this, if strong enough, may develop into an air-entraining vortex. It is erroneous to suppose that such vortices originate at the intake itself, which merely acts as a sink to withdraw water from a particular place at a particular rate. Even the shape and direction in which the intake faces are very minor factors in the phenomenon because the tail of the vortex can turn through large angles with ease.

The process of vortex formation depends on the conservation of angular momentum, since if a ring of water rotation at a particular speed is drawn into a smaller diameter by the suction of the intake, then the rotational velocity must increase correspondingly. Thus it can be seen that provided there is even the slightest rotation far away from the intake, rapid rotational movement near the centre cannot be avoided. Transient disturbances such as eddies do not cause vortices, because rotation cannot be sustained once the whole of the water that was originally rotating has been drawn into the intake.

Rotation in the approaching flow can arise from a number of causes, and of these two are most frequently encountered. They are: (*a*) asymmetry of the intake with respect to the boundaries of the approaching flow, as exemplified in Fig. 1 (a); (*b*) change in the direction of the boundaries immediately upstream of the intake, as in Fig. 1 (*b*).

It is, of course, not always possible to avoid serious rotation in the flow approaching the intake, but fortunately other factors such as depth of water, velocity through the intake and so on, which are usually under the control of the designer, also have a large influence on the formation of vortices and on the swirl at the intake. The effects of factors such as these are discussed below.

The experimental work on which this paper is based was carried out in the laboratories of the British Hydromechanics Research Association.

2. Experimental results

a) *Air-entraining vortices*

A series of experiments was conducted to study the factors influencing the formation of air-entraining vortices at intakes.

Tests were made in simple sump layouts, the water being drawn through the intake by a pump connected to the intake by a flexible pipe of sufficient length to exclude any effects of pre-rotation due to the pump impeller. Intakes of various shapes and dispositions ranging in diameter from 7/8 inch to 30 inches were studied in sumps ranging in width from 6 inches to 8 feet.

Development of air-entraining vortex

In most cases the development of an air-entraining vortex proceeded as follows. When the intake was well submerged and the intake velocity low the vortex appeared first as a small dimple in the free water surface. (Fig. 2). which gradually became deeper: air bubbles would occasionally break away from the bottom of this hole and be carried into the intake as a chain of bubbles. (Fig. 2d). At higher intake velocities the chain of bubbles became a continuous air core extending into the intake. (Fig. 2e). With large submergence of the intake the vortex was located some distance from the pipe and was very stable. quickly reforming if the water surface was disturbed. With small submergence the vortex formed closer to the intake and was less stable in position.

The boundary between vortex-forming and vortex-free conditions is not very precise and the method adopted in these experiments to determine the boundary curve has been to plot on a graph, relating water depth to flow. a large number of points representing vortex-forming and vortex-free conditions. The criterion used was whether. after a reasonable time at steady conditions of depth and flow. any air from the free water surface entered the intake. either continuously or intermittently through the agency of the vortex. Fig. 3 is a typical diagram obtained in this way. the boundary curve being drawn to envelop the vortex-forming region. By this method the envelope could be drawn with reasonable accuracy but isolated vortex-free regions sometimes occurred within the main vortex-forming region. This may be because insufficient time was allowed for the air-entraining vortex to develop or because of the haphazard behaviour of the vortex under critical conditions.

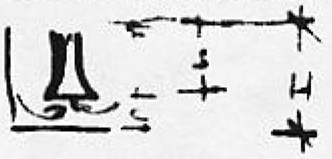
Relation between critical submergence and intake velocity

In all these experiments it has been possible to obtain a boundary curve of the type of Fig. 3 for a given set of boundary conditions and pattern of approaching flow. The shape of the boundary curve varies with the circumstances but in general the curves have one limb tending to become asymptotic to a constant velocity and another limb tending to become asymptotic to a constant depth. In other words there is one region at low intake velocities where the critical submergence is very dependent on velocity through the intake. and another at high intake velocities where the critical submergence is not very dependent on velocity. The transition between the two regions is more abrupt in some cases than in others.

This dependence of the critical submergence on velocity is important in the design both of installations and their models and in the scaling up of the model results to prototype conditions. It will be discussed in more detail later in the paper.

Dependence of critical submergence on the strength of the rotational flow

In tests with a bellmouthed intake on a vertical 4 inch pipe in the centre of an 8 foot square sump the degree of angular momen-



$\frac{c}{d}, \frac{s}{d}, \frac{H}{d}$

tum about a vertical axis through the intake was varied by varying the width of the sump through which the water was allowed to enter. Rotational flow was strongest when the water entered through half the width of the sump and this condition caused the most severe vortices, requiring a critical submergence of 15 diameters to prevent air-entrainment at high velocities, (Fig. 4). With the water entering over the whole width of the sump, i.e. a nominal zero resultant angular momentum, the critical submergence was only 3.5 diameters at high velocities. Thus a fourfold change in the critical submergence at high velocity was effected merely by varying the angular momentum about the intake in the approaching flow.

The effect of the boundaries of the approaching flow

The boundaries of the flow approaching an intake may either be solid boundaries or the boundaries between the flow entering the intake and flow entering a neighbouring intake or going elsewhere, e.g. over the spillway in a hydro-electric scheme. Their shape and direction in relation to the intake determine to a large extent the resultant angular momentum about the intake and thus have the major influence upon the vortex-forming conditions.

The proximity to the intake of solid boundaries such as the walls of a sump or the dam of a hydro-electric scheme has a marked effect on the critical submergence.

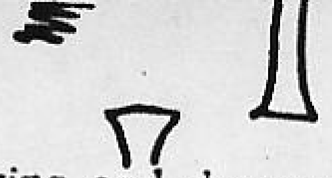
The effects of bottom clearance below a vertical intake pipe with upward flow are shown in Fig. 5, which was obtained from tests with a 4 inch pipe in an 8 foot square sump and a 7/8 inch pipe in a 2 foot square sump with similar entry conditions. The results for the two models were precisely similar and demonstrate that as the bellmouth is raised from the floor the critical submergence decreases, although the actual water depth increases considerably.

When the intake was moved about a sump it was found that the critical submergence at a given velocity was greatest when the intake was nearest the centre of the sump and least when the intake was close to the walls. The critical submergence was smaller for a given size pipe in a smaller sump, and also for a larger pipe in a given size sump. Fig. 6 shows the correlation of the results from the experiments in which the rotational flow was nominally the same, using both different pipes and different sumps, when the pipe is equidistant from two adjacent walls.

The critical submergence is independent of wall clearance when this extends 10 pipe diameters and is approximately proportional to wall clearance when this is less than 5 diameters. A single wall in close proximity to the pipe usually, but not always had as much effect. The results for an inlet in the wall were very similar to those for a vertical pipe close to the wall.

When there are two or more intakes close together drawing from the same body of water the boundaries of the flow to a given intake are sometimes affected by the flow into the neighbouring intakes, and thus the severity of the rotational flow approaching the intake may be dependent on the amount of flow into the other intakes.

Experiments show that the shape of the intake has very little effect on vortex forma-



tion. Upward facing and downward facing vertical intakes behave very much alike, but with horizontal intakes the disposition of the intake relative to the vortex zone in the sump appears to be important.

b) *Swirl in the intake*

A series of experiments was carried out to determine the effect of a number of variables on the severity of the swirling flow in the intake. Suction sumps of various shapes were used in conjunction with moveable suction pipes arranged in a vertical position.

Pitot-tube traverses across the pipe diameter showed that the direction of flow was not always steady, due to turbulence and minor changes in flow pattern in the sump. It was clear, however, that the distribution of the tangential component of velocity across the pipe inlet approximated to that of a free vortex (i. e. velocity inversely proportional to radius) as in the sump itself, while further along the pipe the swirl corresponded more nearly to solid body rotation (velocity proportional to radius).

In the latter position, a vane allowed to rotate about the pipe axis was found to give a fair measure of the swirl at this point, and for convenience this method of measurement was adopted. Comparison of the true flow angle measured by pitot-tube, and the mean angle measured by the vane is made in Fig. 7; both instruments were located 4 diameters downstream of the intake.

Swirl angles in the pipe were found to be independent of the flow, but considerably affected by the depth of water in the sump. This can be seen in Fig. 8, where the swirl is expressed non-dimensionally both as the pitch of the spiral, and as the equivalent angle of flow at the pipe wall. The scatter of the test points is due to turbulence in the sump, and could have been reduced somewhat by taking measurements over longer time intervals. It can be seen that swirl angles are unaffected by the formation of air-entraining vortices, in spite of the fact that, with the intake facing downwards, water associated with the vortex enters the intake rotating in the opposite sense to that of the main body of water. In sumps which were very nearly symmetrical, the swirl increased abruptly and considerably as the water was lowered beyond a particular level, corresponding to a sudden change in flow pattern in the sump. (Fig. 8b). Boundary walls in close proximity to the intake improved the flow conditions, and had much the same influence on swirl as on air-entrainment.

These results were found to be the same whether the intake faced upwards or downwards, so long as the axis was vertical. When however the axis was horizontal, rotation in the oncoming water did not cause swirling flow in the intake. The only conditions under which swirl occurred in a horizontal pipe corresponded to existence of angular momentum in a vertical plane within the sump. For instance with the layout shown in Fig. 9 swirl angles were comparable to those obtained with vertical intakes. Inclined intakes produced effects which were much more complex because the separate rotations in the two planes interfered with each other. This aspect of the problem was not pursued experimentally.

Since many factors influence both vortices and swirl in a similar manner, it is not surprising to find a relation existing between for swirl

the two effects, and it appears that measured swirl angles do not exceed 5° in the absence of air-entraining vortices. Taking into account the fact that this figure is itself artificially high owing to the method of measurement it seems unlikely that in most practical cases the effects of swirl by itself will be serious. However, devices can be employed to prevent vortices which do not at the same time diminish the swirl, so that it is possible in extreme or unusual cases for swirl to have a significant effect on machine performance.

3. Prevention of vortices and swirl in existing installations

When vortices are discovered in existing installations the remedies that can be employed are often limited to minor modifications. It may be impracticable to alter the size or depth of the intake, or to modify the boundaries of the approaching flow: under these conditions, remedies fall into two categories (a) those which obstruct the free rotation of the water in the neighbourhood of the intake (b) those which deflect the tail of the vor[illegible] intake. Devices of this sort are illustrated in Fig. 10. It will be appreciated that none of these remedies strike at the root of the trouble, and for this reason they may have little effect on the magnitude of the swirl in the intake.

A different approach is appropriate to prevent swirl in the intake, for in this case it is necessary to destroy the angular momentum causing the swirl. In the event of it being impracticable to make major modifications to the layout, guide vanes at the intake may be effective in reducing the swirl angles. Experiments in a model sump showed that cruciform guide [illegible] were the most effective remedy and optimum conditions occurred when these were situated 2 or 3 diameters downstream of the intake, and were of length at least equal to the intake diameter. By this means swirl could be eliminated completely, though the flow leaving the guide vanes tended to be highly turbulent. Fins attached to the outside of the pipe had to be very large to be effective; vanes fitted between the floor of the sump and the intake were not effective in the range of conditions under which local vortices occurred, i. e. in deep water. None of these fittings was effective in reducing the entrainment of air through a vortex.

4. Experiments with models of installations

Small-scale models of several existing or proposed pump installations and a few hydro-electric schemes have been used to investigate the possibilities of air-entrainment at the intakes. These have proved valuable in assessing the merits of the design and indicating possible improvements, although the scale was sometimes too small to give accurate data about critical submergences. Some examples and results of such model tests are given below. A few common forms of pump sumps with two intakes are shown together with their characteristic diagrams in Fig. 11.

In the simplest form, Fig. 11a, where the sump is the same width as the approach channel, and the pumps are on a line normal to the flow, the critical submergence was found to be greatly dependent on the actual size of the sump. This was also the case when the approach channel was narrower than the sump as Fig. 11b, but owing to the sudden expansion into the sump, vortices formed much more readily. For example with a sump of width 16 diameters, the critical submergence in arrangement (*b*) was double that with arrangement (*a*). The fitting of baffle walls as in Fig. 11b to make the expansion less sudden, halved the critical submergence when the sump width was 8 diameters.

In Figs. 11c and 11d, the pumps were in a line parallel with the flow. In case (*c*) the swirl was very slight and the vortices therefore not severe, the critical submergence not exceeding 1.5 pipe diameters. When operating alone less submergence was required at intake No. 2 than at No. 1, because of its closer proximity to the end wall, and when both intakes were operating the vortices were less prone to occur at the first intake as the flow past this swept away any vortex dimples in the vicinity.

When the water entered the sump obliquely, as in Fig. 11d, the conditions were much more severe because separation from the wall set up a large swirl. The critical submergence when only one intake was operating at a time was about 5.5 diameters, but with equal flows through both intakes the flow patterns were such in this particular sump that no air entrainment occurred.

Tests on a scale model of an existing three pump land drainage installation shown in Fig. 12 gave results in accordance with observations of vortex conditions made at the pumping station. Intake No. 3 did not produce such strong vortices as intake No. 1, because of the raised platform adjacent to inlet 3, which filled in the dead water region at the end of the sump.

The effects of various modifications to improve conditions in the sump are shown in Fig. 12a. The best results were obtained with baffle walls placed within 1.5 diameters of each suction pipe. Some effects of altering the shape and disposition of the intakes can be seen by comparing curves *A*, *B*, *C* and *D* of Fig. 12a. Enlargement of the pipe to reduce the intake velocity was the most effective.

An example of a well designed triple-pump sump is shown in Fig. 12b. Model tests indicated that the expansion was not gradual enough to avoid separation entirely, but the critical submergence was low and did not under any conditions exceed twice the diameter of the smaller suction inlets.

Fig. 13a shows a proposed design of forebay with multiple turbine intakes in which the water depth and submergence were relatively small. Tests with a small scale model of the complete forebay with equal flows through each intake indicated that vortices were likely to form at the corner of each intake, when the submergence was less than 2 diameters above the soffit of the horizontal penstock.

An interesting arrangement of 3 turbines intakes on a proposed hydro-electric scheme is shown in Fig. 13b, where the intakes are set in the face of a boundary which is parallel to the general direction of the approaching flow. The critical submergence for the intakes *A*, *B* and *C*, when operating alone, were 2.35, 2.75 and 5 diameters respectively. These critical submergences are directly proportional to the distance from the dam face and support the design principle already indicated that the closer the intake is to the wall the smaller is the cover necessary to prevent air-entraining vortices.

When intake *C* was operating in conjunction with intake *A*, the critical submergence required to prevent air-entrainment at *C* was reduced from 5 diameters to 3.25 diameters. Flow into intake *B* did not affect the critical submergence at intake *C*, but a strong vortex developed at intake *B* which persisted, even when the vortex at *C* was stopped by a baffle, up to much higher submergences than the critical submergence for intake *B* operating alone. When intake *B* was operating together with intake *A* it made conditions a little worse at intake *A* and increased the critical submergence for *A* from 2.35 to 2.75 diameters. When all intakes were operating together the critical submergence required was 2.85 diameters above the higher intakes.

5. Scale effects

With many types of scale model, flow conditions can be made similar to those in the prototype by choosing velocities to accord with the appropriate dimensionless number, and since air-entraining vortices appear to belong to the category of free-surface problems, one would expect flow at equal Froude number to give the desired result. This does not seem to be the case. In small models, substantially higher velocities than those given by the square root of the linear scale have been found to be necessary, and there is evidence that in a particular size range air-entraining vortices only occur under similar submergence conditions when prototype velocities are used.

This evidence is provided by the results of several laboratory experiments covering a scale ratio of 8:1; some of these are reproduced in Fig. 14. From Fig. 14a there would appear to be some scale effect with very small submergences, since the differences in velocity are greater than can be attributed to error of measurement, but at the greater depths conditions were similar at exactly equal velocities. With the sumps shown in Fig. 14b the discrepancies were of small magnitude and random nature, suggesting that no scale effect existed.

Scale ratios up to 16:1 have been obtained from full-scale installations, but in no case has it been possible to record conditions over a wide range of flow or water depth. Accurate measurement of flow was often impossible. Nevertheless in the installation shown in Fig. 14c a spot result was recorded with satisfactory accuracy, and this has been compared with corresponding model data. It is clear that while flow at equal velocities will, for the point considered, bring the model into line with the prototype, flow at equal Froude numbers will not.

It is difficult to believe, however, that this equal-velocity rule is capable of extrapolation up to very large installations, for this would lead one to expect enormous vortices, extending perhaps deeper than 100 ft, to occur occasionally at intakes of hydro-electric or pump-storage schemes. So far as the authors are aware existence of such vortices has not been reported, and the largest for which they have reliable evidence extended only 18 ft deep. This suggests a change in law as the size of the installation increases beyond the range of these experiments.

The present results tend to accord with the experience of other investigators. For instance IVERSEN (1935) showed that model velocities based on the Froude number were far too low to give comparable conditions, and FRASER (1953) went so far as to say that «satisfactory results have been obtained if the model is designed with the same flow velocities as in the prototype». This practice errs, if at all, on the side of safety.

It may well be that while the velocity required to form a dimple in the water surface follows Froude's laws, the local velocity required to drag air from the tail of the vortex is substantially unaffected by the scale of the phenomenon. Certainly it has been noticed that the surface dimple proceding the vortex appears at a lower velocity in the model than in the prototype.

In many other ways the vortex and sink flow appear to be separate effects, each making varying contributions to the conveyance of air from the free surface to the intake. At low flows the strength of the rotation seems to be of little importance, the intake velocity being the predominating factor, but at high flows the reverse is true and the strength of the rotation is of much greater importance than the intake velocity. It is therefore surprising that under the latter conditions the submergence should be so greatly affected by the area of the intake for, except very near to the intake, the flow patterns should be identical for the same flow. However, attempts to correlate the results on a basis of quantity flow proved fruitless and in the absence of any wall effects greater depths were usually necessary when water at a low velocity entered a large intake than when the same quantity of water entered a small intake. This is one of the conflicting facts concerning the behaviour of vortices that is not easily explained.

So far as models to reproduce swirling flow in the intake are concerned, there should be no scale effect, and geometrically similar systems will result in identical flow patterns provided the flow in each is in the turbulent region.

6. Conclusions

All investigators of vortex phenomenon agree that the process of vortex formation is complex, and enough has been written in this paper to show that many facts still remain unexplained.

Nevertheless, the data now accumulated are sufficient to indicate the practical influence of the relevant variables, and the known facts concerning these are summarised below:

1. Air-entraining vortices and swirling flow at the intake both arise from rotation in the water supplying the intake, the magnitude of which depends on the position of the intake relative to the direction and boundaries of the approaching flow.
2. In extreme cases over 10 % of the flow entering the intake consists of air and swirl angles up to 40° can be realised.
3. Severity of both air-entraining vortices and swirling flow is diminished by (a) reducing the strength of the rotational flow in the approaching water; (*b*) increasing the area of the intake; (*c*) increasing the depth of water; (*d*) siting vertical or slightly sloping walls close to the intake.
4. The only remedies that are equally satisfactory for both troubles. are guide

vanes. Floating rafts and baffles may prevent vortices but leave swirl unaffected. Vanes in the intakes can reduce swirl but do not prevent air-entrainment.

5. For intakes up to 3 ft diameter, scale models larger than 1/16 scale are capable of providing accurate quantitative data provided velocities in the model are equal to those in the prototype. It is also probable that smaller models than this give adequately reliable data, but the limit is not known; fortunately models tend to err on the safe side. The laws applying to intakes larger than 3 ft are also not completely understood. Air-entrainment is usually accompanied by loud noise and by vibration of the less rigid parts of the system, so that it is unlikely to occur unnoticed. If no air-entrainment is apparent, swirling flow is unlikely to be significant.

Acknowledgment

Results of research carried out at the British Hydromechanics Research Association are reproduced by kind permission of the Council of the Association. Some of the figures are based on those already published in the paper by DENNY in the Proceedings of the Institution of Mechanical Engineers. Vol. 170. No. 2. 1956.

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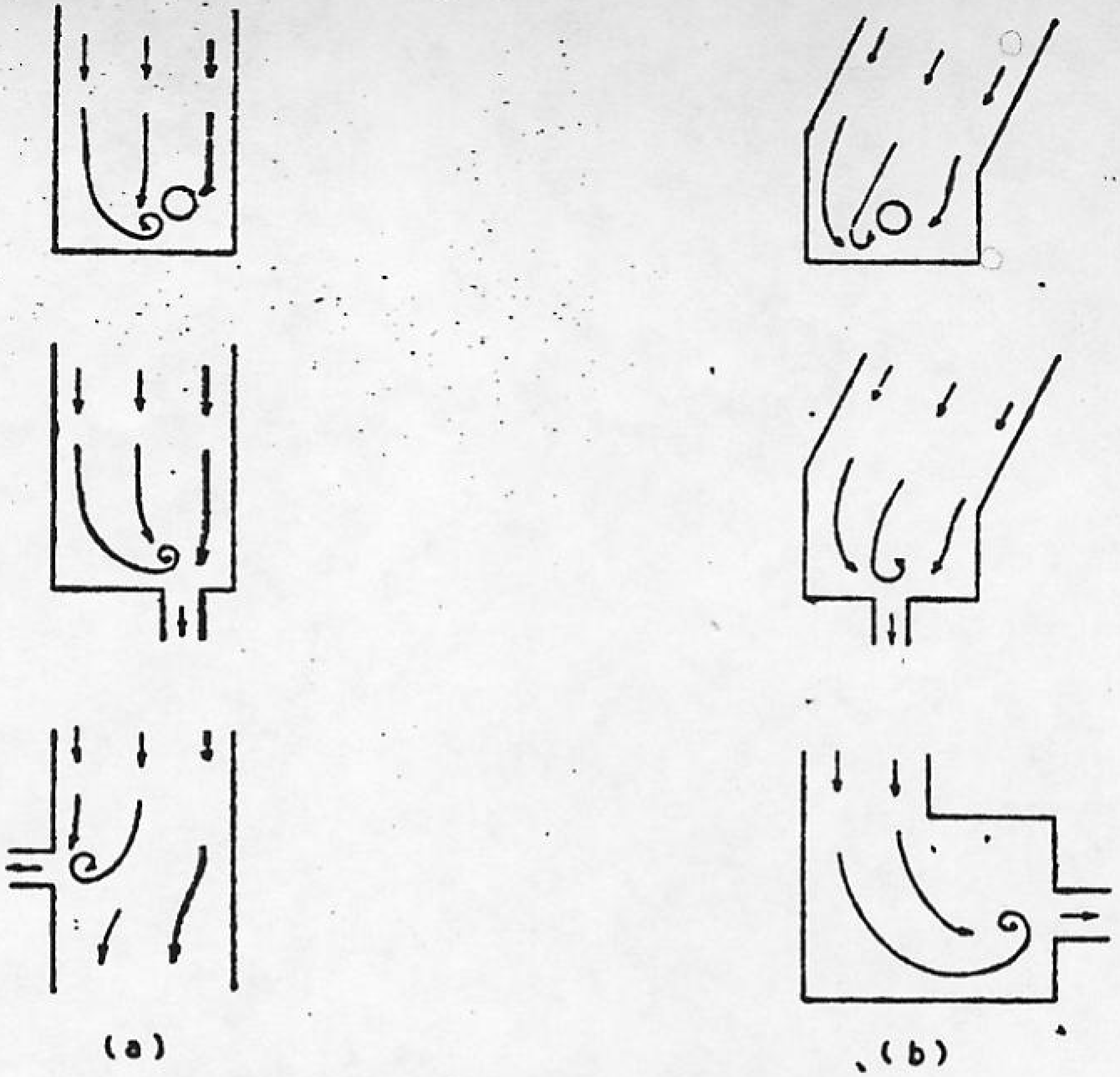


Fig. 1 — Rotational flow arising from (a) asymmetry and (b) change in direction of boundaries. Sketches show plan view

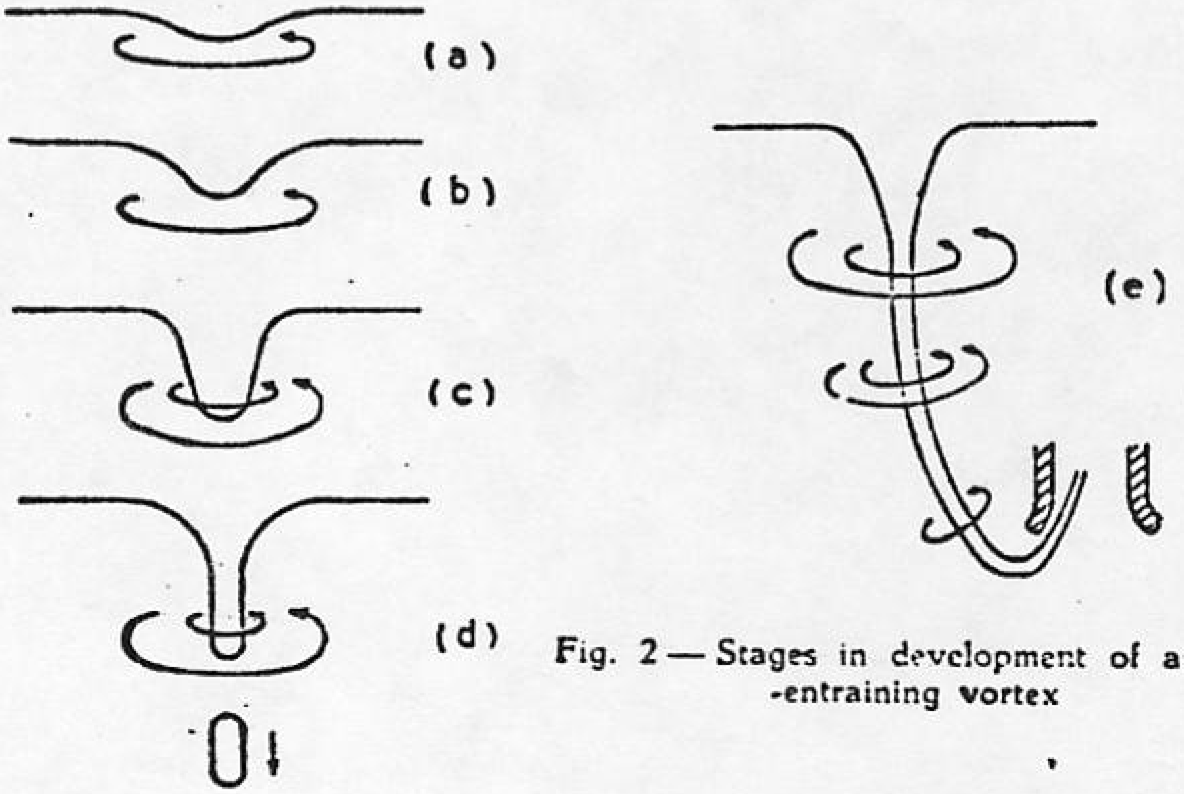


Fig. 2 — Stages in development of an air-entraining vortex

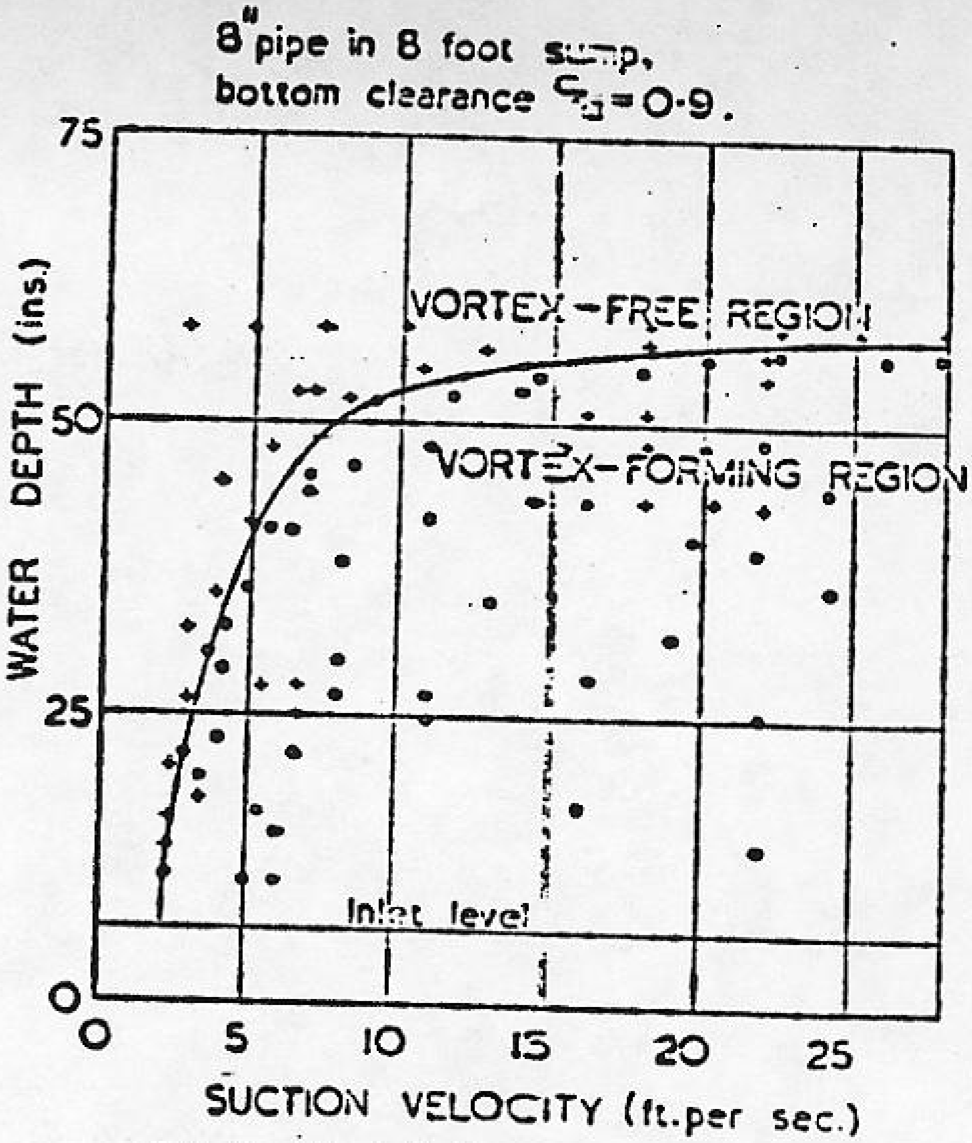


Fig. 3—Typical plot of vortex data

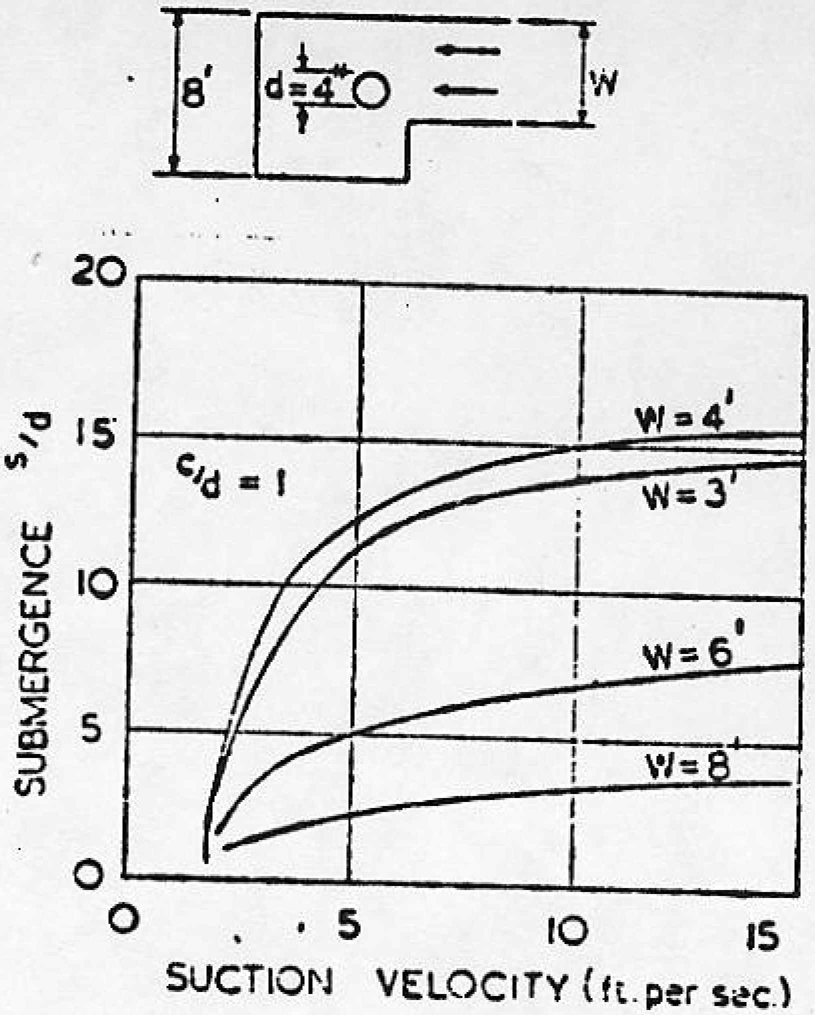


Fig. 4—Effect of rotational flow

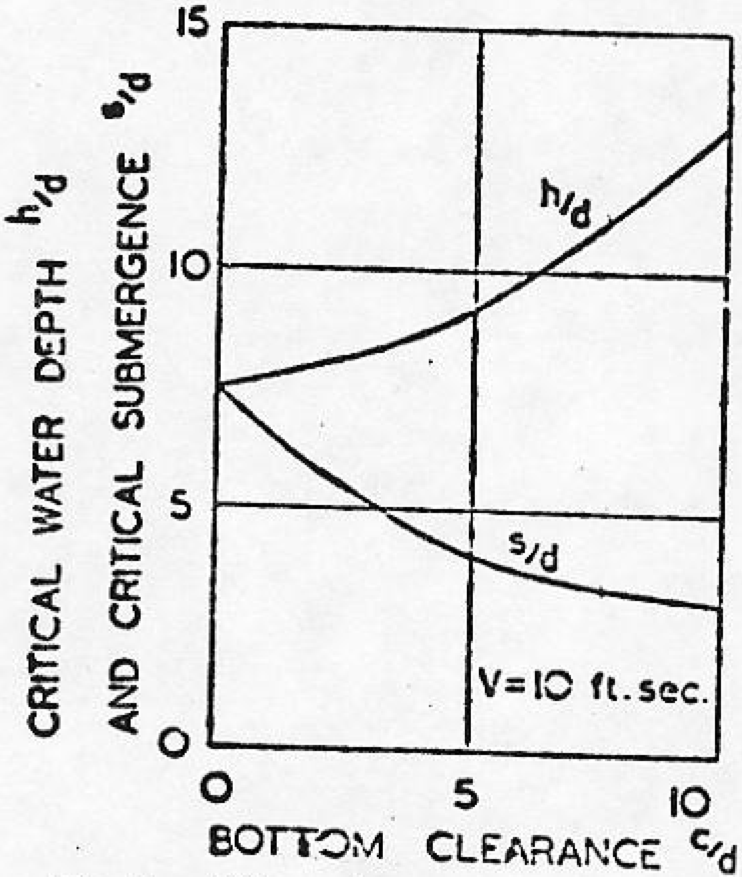


Fig. 5—Effect of bottom clearance

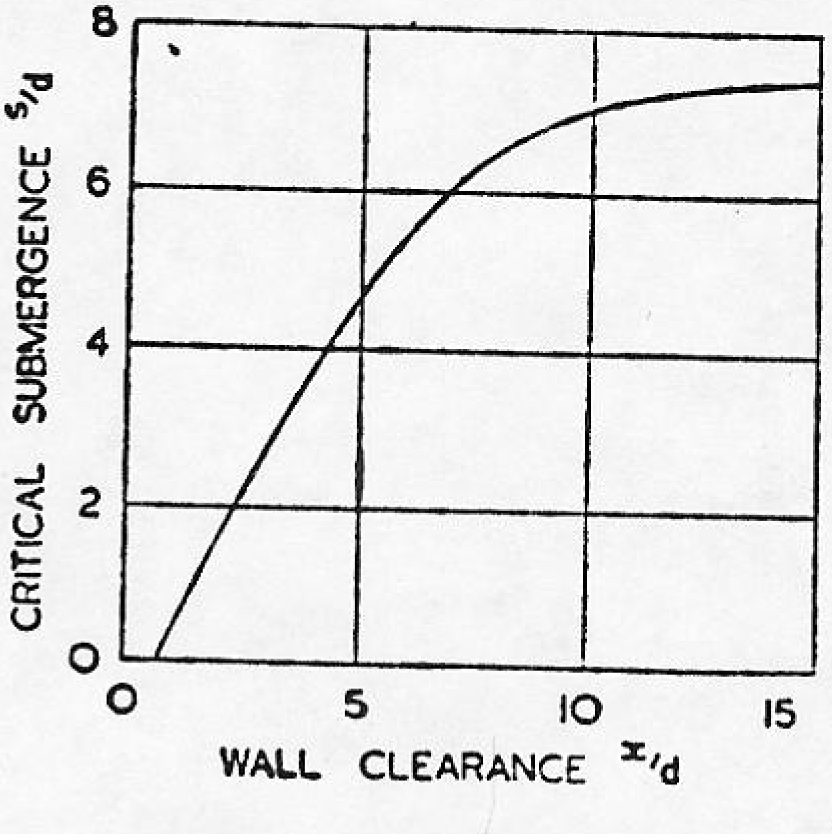


Fig. 6—Effect of wall clearances for pipes of various sizes situated centrally within similar sumps

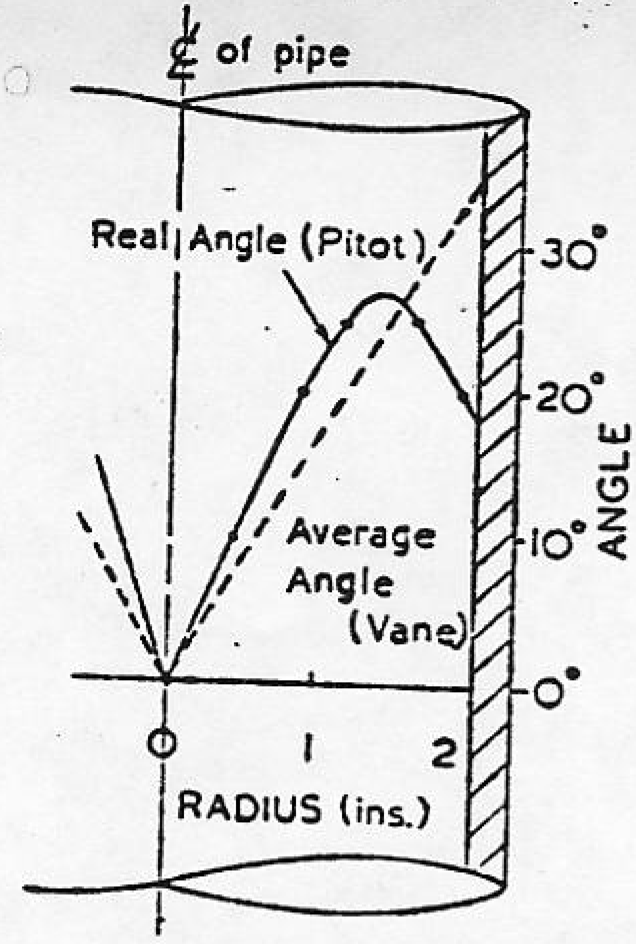


Fig. 7 — Measurements of distribution of swirl angle across a suction pipe

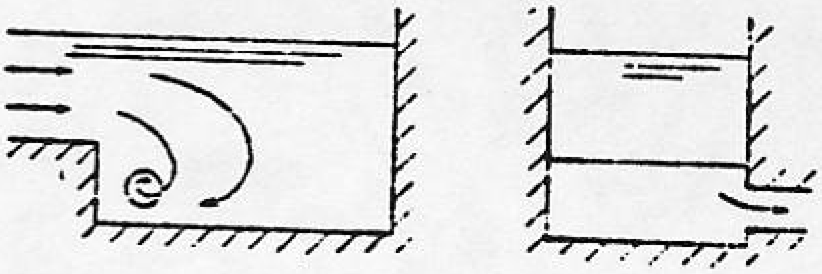


Fig. 9 — Swirl with a horizontal axis

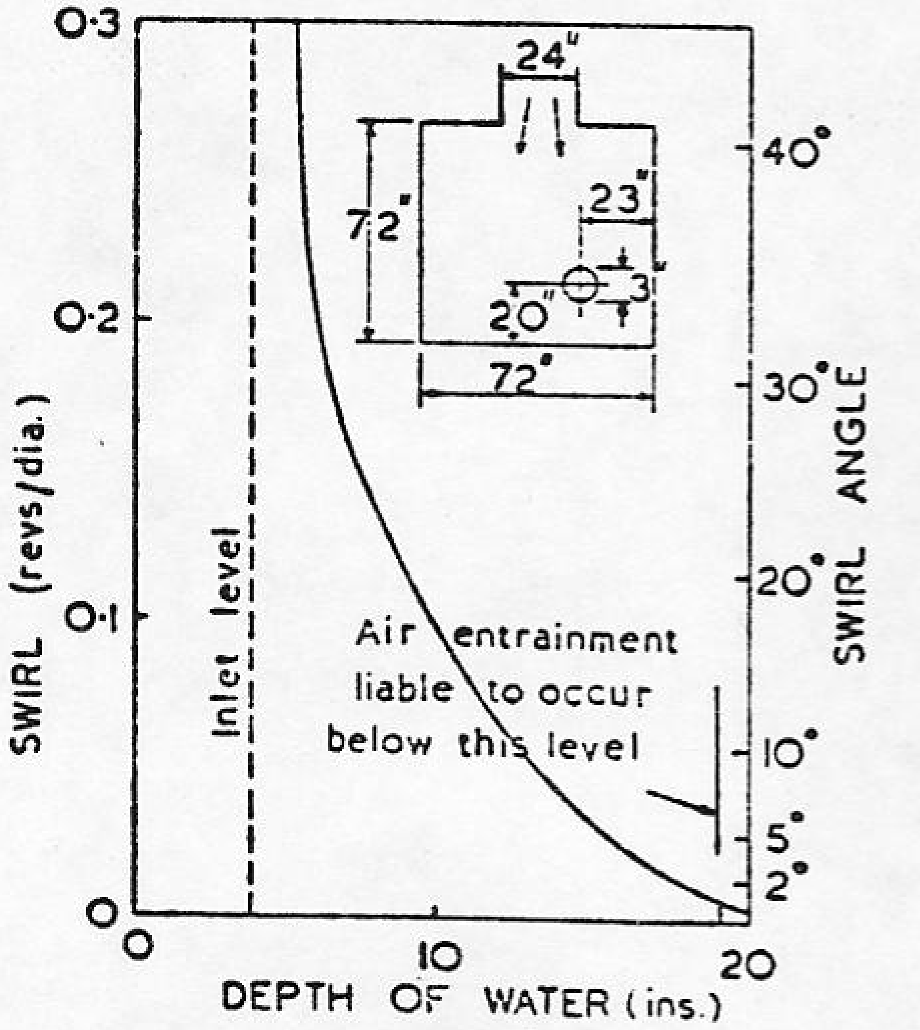


Fig. 8 (a) — Effect of depth of water on swirling flow in a suction pipe

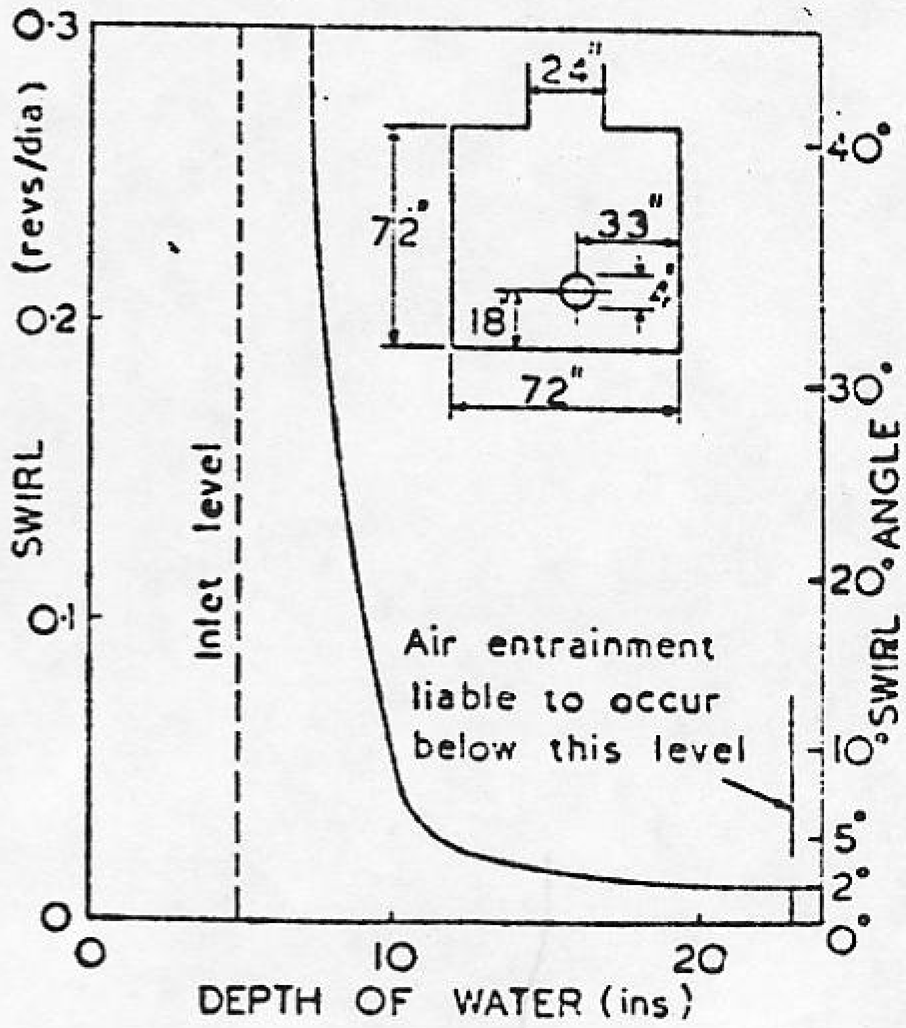


Fig. 8 (b) —

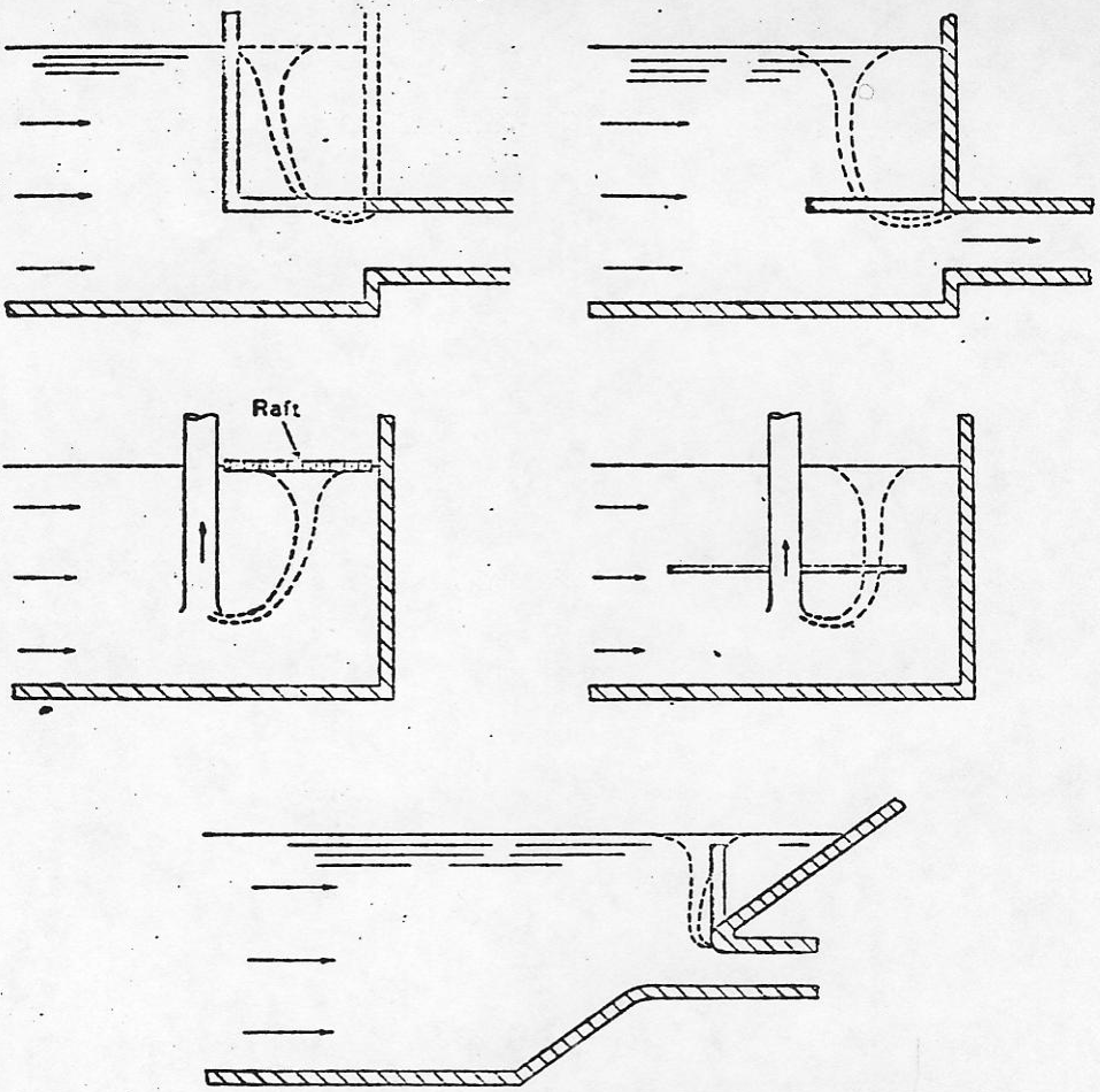


Fig. 10 — Prevention of air entrainment by means of baffles, walls, or floating rafts

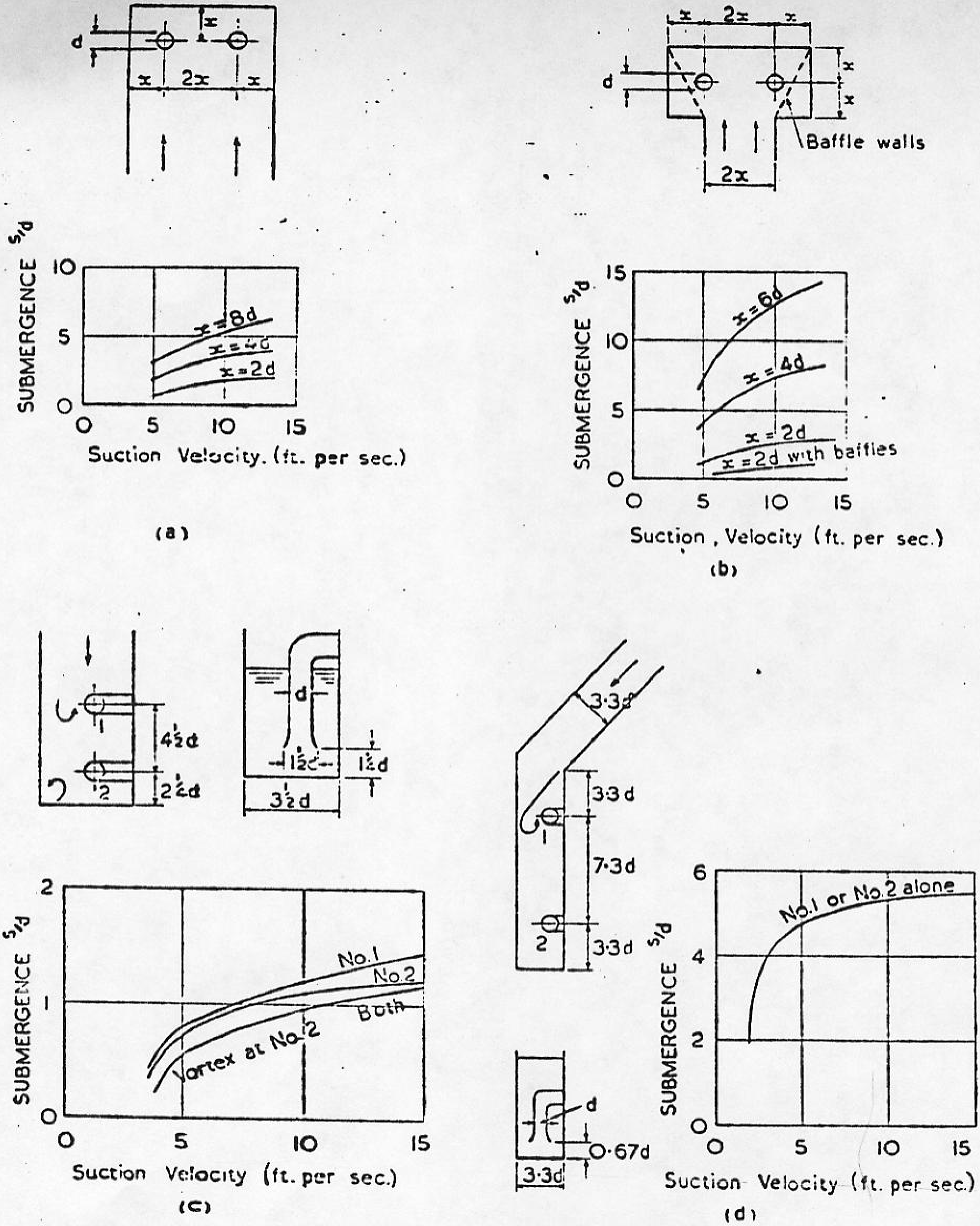
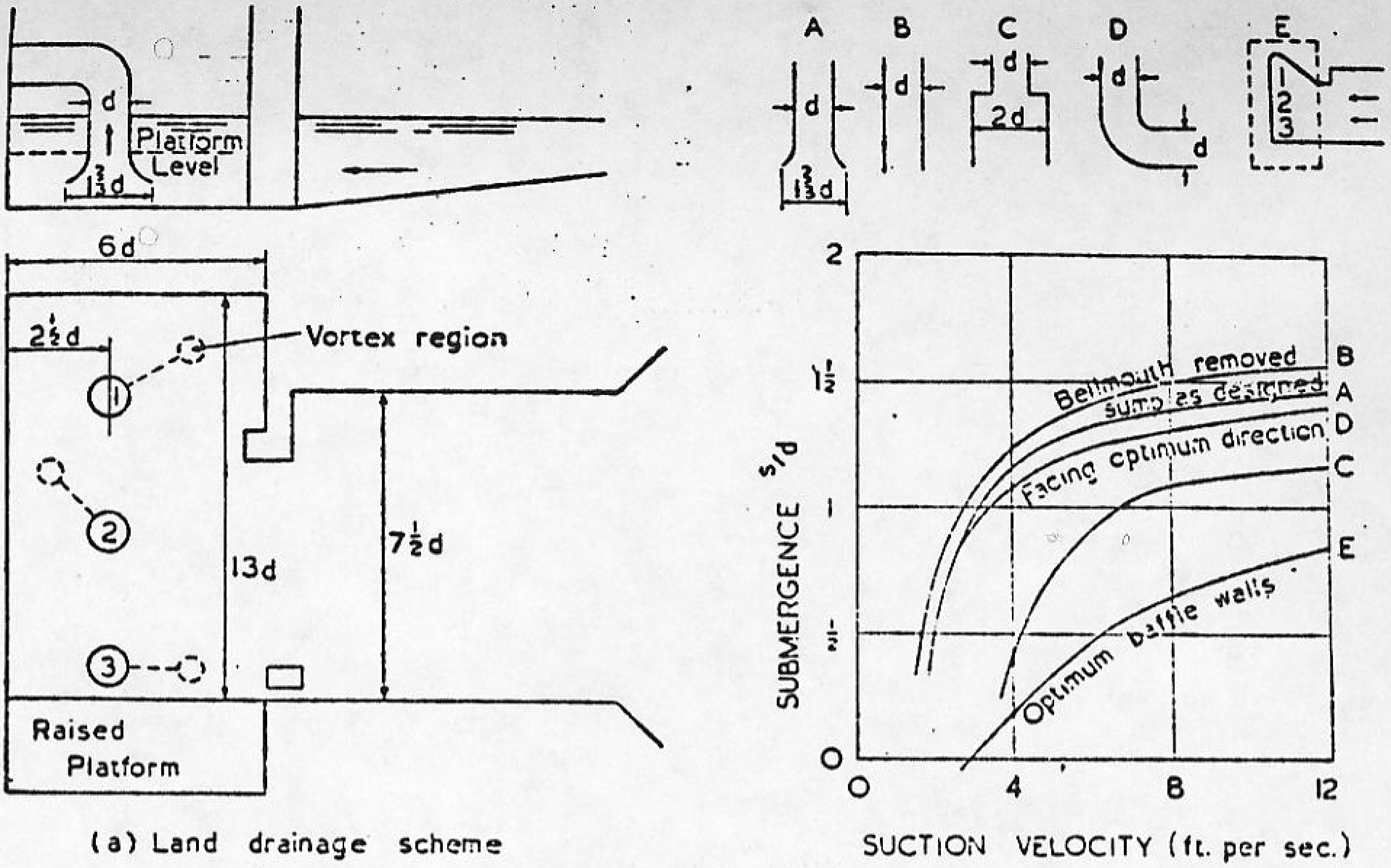
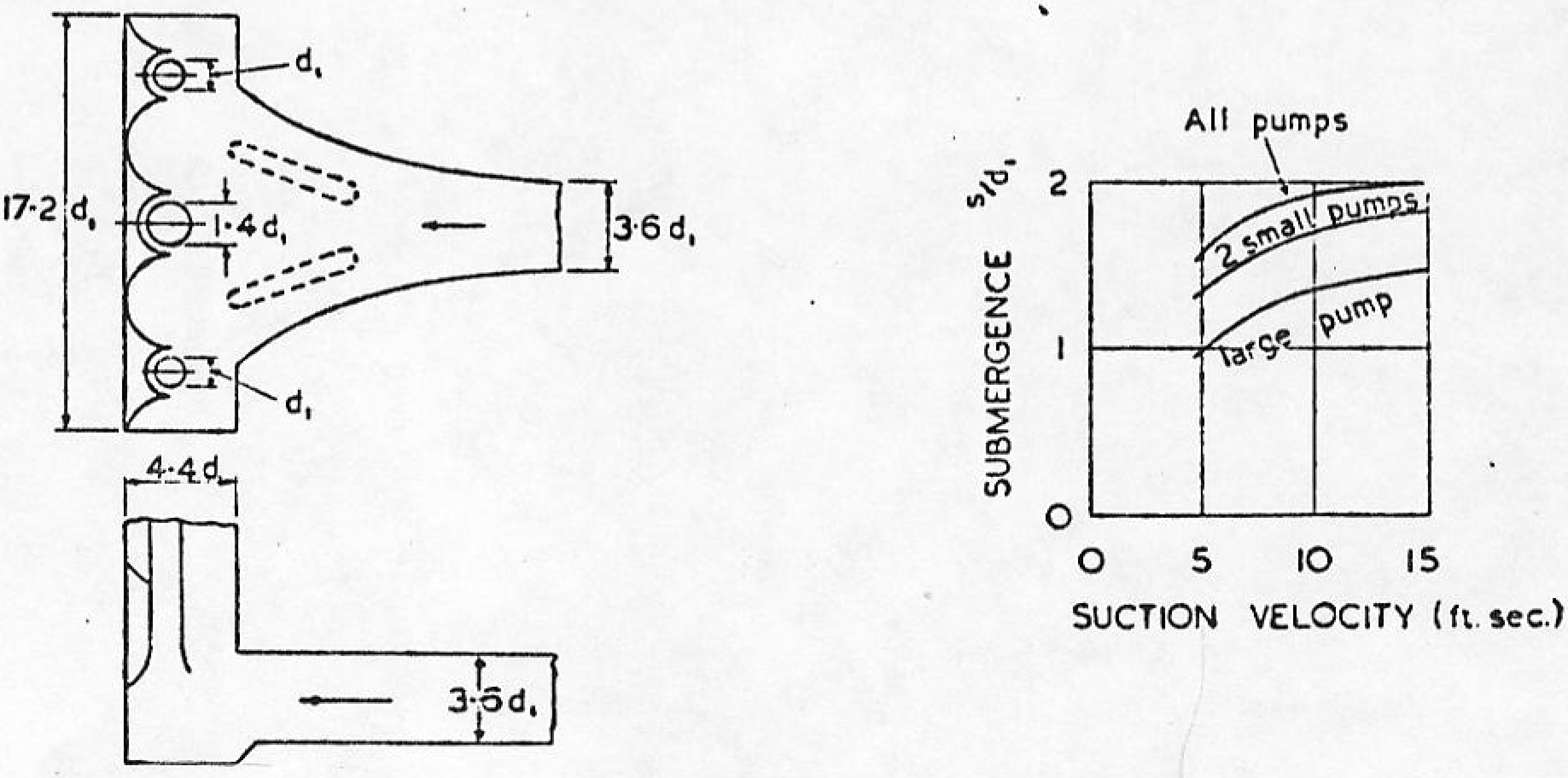


Fig. 11 — Characteristics of various model sumps

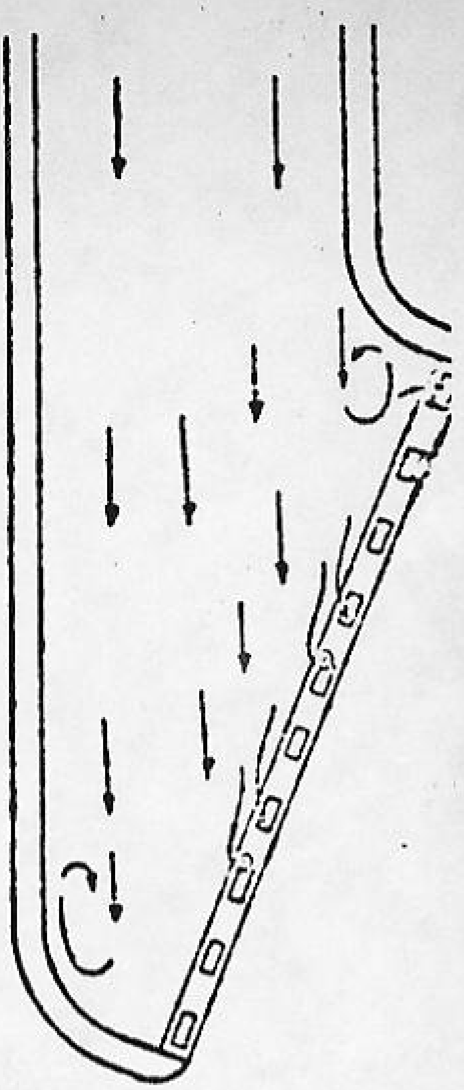


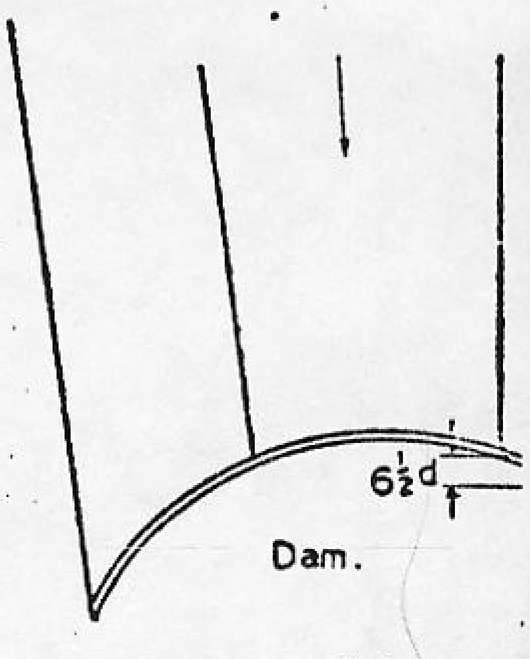
(a) Land drainage scheme



(b) Sea-water pumps

Fig. 12 — Model characteristics of triple pump sumps





(b)

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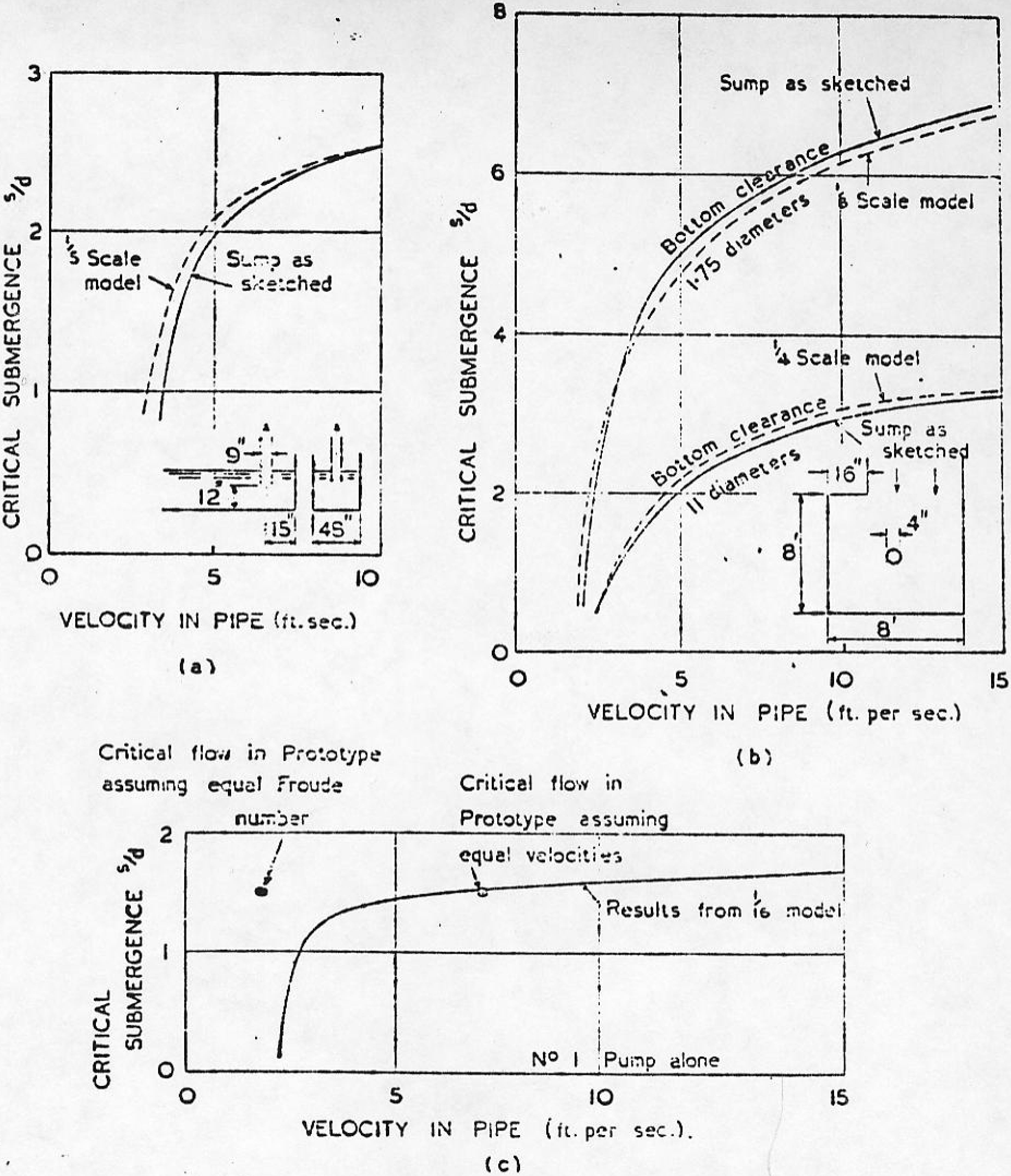

(a)

(b)

(c)

Fig. 14 — Scale effects (a) and (b) laboratory model sumps