UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 224

AN EXPERIMENTAL STUDY OF CRITICAL SUBMERGENCE TO AVOID FREE-SURFACE VORTICES AT VERTICAL INTAKES

by

Alan J. Rindels and John S. Gulliver

Prepared for

LEGISLATIVE COMMISSION ON MINNESOTA RESOURCES
STATE OF MINNESOTA
St. Paul, Minnesota

June, 1983

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ABSTRACT

Free surface vortices at intakes can cause excessive vibration, efficiency loss, structural damage, and flow reduction in hydroturbines, pumps, culverts, etc. They can also be a safety hazard and a potential loss of life. One of the major problems encountered during intake design is the specification of submergence and other design parameters in order to avoid strong free surface vortex formation. A properly conceived model study will determine whether free surface vortices are likely to occur. Before that point, however, the engineer needs to develop a preliminary design and then decide if a model study is needed.

In order to assist in preliminary intake design, a plot of dimensionless submergence versus intake Froude number is presented for a number of vertical and horizontal intakes from both field and laboratory observations. The pilot is divided into two regions: 1) a region where intake vortices are unlikely and a model study is not required except with extremely poor approach conditions, and 2) a region with a good possibility of intake vortices, and a model study is recommended.

Region 2, where intake vortices are a good possibility, is very large, encompassing many intake facilities. This is because minimum intake submergence to avoid vortex formation is highly dependent upon approach conditions, which are site specific. In order to add some clarity to this limited design criteria, an experimental study was undertaken which focused upon typical intake approach conditions. Most hydropower intakes have a forebay to avoid high circulation near the intake, so the experimental study simulated approach conditions with a forebay or approach channel of varying length and width.

The experiments were limited to vertical bellmouth intakes. The tendency for vortex formation is enhanced by separation around the leading edge of the approach channel walls. A long, narrow forebay will reduce the tendency for vortex formation.

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I. INTRODUCTION

Many of the problems which can occur at closed conduit intakes are a consequence of a free surface vortex. Free surface vortices are a very highly organized turbulent free-surface flow phenomena which occurs due to the residual angular momentum in the flow at a closed conduit intake. They occur commonly at free-surface flows into a closed conduit, such as a sink or bathtub drain. In large closed conduit intakes, however, free surface vortices are a severe problem which should be avoided. Free surface vortices have been found to cause flow reductions, vibrations, structural damage, surging due to formation and dissipation of vortices, and a loss of efficiency in turbines and pumps. They have also been found to be a safety hazard at lock intakes [1]*.

The two examples of free surface vortices given in Photos 1 and 2 (see Sect. III) help illustrate the reasons for these problems. An intake designed for a smooth and straight flow will experience a highly swirling flow when vortices are present. The swirl will give unexpected flow patterns into a turbine or pump, which reduces efficiency, causes cavitation to develop, and may lead to the development of resonance vibration with the structural components of the machine. A free surface vortex with an air core will also cause a significant reduction in the flow capacity of the intake.

Most of the research work on free-surface vortices to date has been performed on a site-specific basis where a hydraulic model study is performed for a given hydroelectric plant, pumping station, navigation lock, or spillway intake to determine whether vortices will be present. Very little research has been performed which furnishes submergence requirements to prevent vortex formation. These design criteria could be used in intake design prior to, or possibly in place of, a model study.

The need for this generic design criteria is great. First, the engineer currently has little information which may be used for intake design before a hydraulic model study is undertaken. Second, many small hydraulic structures cannot afford the cost and time delay associated with hydraulic model studies. Many of these small structures are currently designed with the "hope and prayer" that free-surface vortices do not occur. This second problem is especially apparent in the upcoming period of small hydropower development in the United States. The U. S. Army Corps of Engineers [2] estimates that there are 4800 small hydropower sites (less than 15 MW) in the United States with development potential. These sites will be built with a typical design-construct period of between 1 and 4 years. The comparative cost and time required for an intake model study is significant.

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*Numbers in brackets indicate references on page 76.

Photo 1. Vortex which formed at Horspranget, Sweden, hydropower intake on August 15, 1949, taken from Rahm [3].

This report addresses the problem of intake design criteria for small hydroelectric facilities. Literature information on vortex formation at field and model intakes is first compiled and presented to give "intake guidelines" for design engineers. These intake guidelines provide a means of comparing a given intake design with past experience and will give a qualitative assessment of whether free-surface vortices may occur. The second part of the report describes experimental research undertaken to give specific design criteria for intakes. The experimental research is limited to vertical intakes with an approach canal and is the beginning of a more extensive program which is needed to adequately address the problem. The experimental program addresses the effects of approach canal length and the angle of flow into the approach canal on free surface vortex formation.

II. REVIEW

A. Parameters Influencing Free Surface Vortices

1. Dimensional Analysis

In this section a dimensional analysis will be performed with conclusions drawn from the literature to determine the important parameters influencing vortex formation at horizontal as well as vertical intakes. Most investigators have focused upon a critical submergence, S_c , also known as the minimum submergence. Jain et al. [4] defined critical submergence as the smallest depth at which strong and objectionable vortices will not form. If the intake is set such that $S < S_c$, a vortex will form, whereas if a $S \geqslant S_c$, a vortex will not form. This definition implies that air entraining vortices are the only types of vortices detrimental to pumps or turbines. Sweeny et al. [5] state that at pump intakes no organized or subsurface vortices greater than surface dimpling, or subsurface swirl, can be allowed. A similar criteria is appropriate for hydroelectric intakes, since the flow through the hydromachine is similar. The one difference from a pump is that a turbine has guide vanes upstream of the runner which may eliminate a small swirl. The amount of swirl allowed before impacting turbine performance, however, has not been documented. The conservative approach is to allow no subsurface swirl at hydroplant intakes.

The dimensional analysis presented here considers the various pertinent variables influencing the critical submergence of the intake structures located in the open flume arrangement shown in Fig. 1. Since the critical submergence is the parameter of interest, it is the dependent parameter of the analysis. Thus, the functional relationship can be written for S_c as

$$S_c = f\,(D', D_o, Q, \Gamma, \rho, \mu, \sigma, g, \delta_i) \qquad (1)$$

where d = diameter of the pipe intake,

D_o = diameter of the bellmouth intake,

Q = discharge,

Γ = circulation,

ρ = density of the fluid,

μ = dynamic viscosity,

σ = surface tension of the fluid,

g = acceleration due to gravity,

S_i = length parameter, distance from side walls, length of approach side walls, height of the bellmouth, etc.

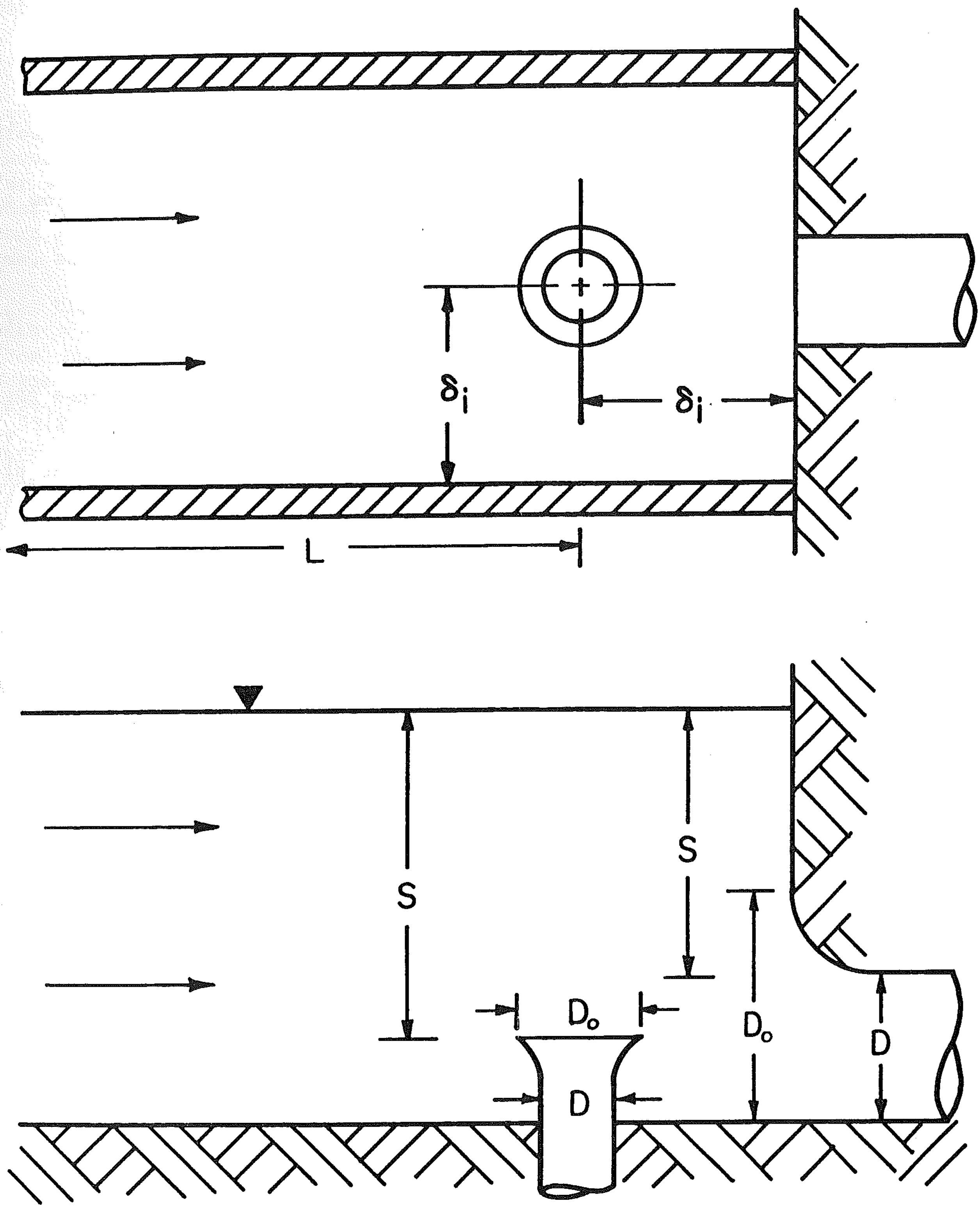


Fig. 1. Schematic representation of horizontal and vertical intake configurations (both incorporated into each sketch).

With ρ , Q, and D as the repeating variables this can be simplified using Buckingham's π theorem to:

$$\frac{S_c}{d} = f\left[\frac{D_o}{d} , \frac{Q}{\nu D} , \frac{\Gamma D}{Q} , \frac{Q}{d^2\sqrt{gD}} , \frac{\rho Q^2}{\sigma D^3} , \frac{\delta_i}{D} \right] i = 1,...n \qquad (2)$$

Since the ratio D_o/D is usually held constant, it can be dropped from the analysis. This reduces the functional relationship Eq. (2) to:

$$\frac{S_c}{d} = f_2\left[\frac{Q}{\nu D} , \frac{\Gamma D}{Q} , \frac{Q}{D^2\sqrt{gD}} , \frac{\rho Q^3}{\sigma D^3} , \frac{\delta_i}{D} \right] i = 1,...n \qquad (3)$$

Many researchers have investigated the relative significance of these parameters in free surface vortices with a cylindrical tank and an outlet in the center of the tank floor [4, 6, and 7]. The circulation of the outlet can be adjusted by using vanes [4, 6] or using jets issuing from the side of the tank [7]. With this type of apparatus, Γ , the circulation is a parameter controlled by the investigator, and can be calculated with the following equation:

$$\Gamma = 2\pi R V_\theta \qquad (4)$$

where v_r = radius of the outer rings, or outside of the tank,

V_θ = angular velocity of the fluid leaving the guide vanes or the jet.

2. Surface Tension

Many experimental studies have indicated that surface tension effects are negligible [4, 6, 8 and 9]. Dagget and Keulegan [6] using a cylindrical tank apparatus and two separate fluids found that in the range of Reynolds number ($Q/D\nu$) from $3\text{x}10^3$ to $7\text{x}10^5$ surface tension does not affect vortex formation. Jain et al. [4] concluded that for a cylindrical tank in the region of $120 < \rho(V^2D/\sigma) < 34{,}000$ that surface tension effects are negligible. Yildrim and Jain [10] used an analytical approach to the dynamics of a rotating fluid element and found that surface tension is an important parameter near the core, and at low values of circulation. Anwar [8] found that for horizontal and vertical intakes in a long flume, surface tension effects are negligible when the Weber number, $W = \rho V^2h/\sigma$, is greater than $1.5\text{x}10^4$, where h is the submergence based on the centerline of the intake. Furthermore, Anwar concluded surface tension is an important parameter at $W < 1.5\text{x}10^4$ only when a surface depression exists, such as a dimple. If the water surface remains flat, surface tension is negligible. Therefore, the literature for the most part concludes that surface tension can be neglected if $\rho V^2D/\sigma$ is greater than 120, of if $\rho V^2h/\sigma$

is greater than $1.5x10^4$, whichever of the two criterion is the most conservative.

3. Viscous Effects

Many investigators have concluded that viscous forces in and around the intake can be ignored if the Reynolds number is large. Each investigator, however, has found a different value of the Reynolds number for which these effects are negligible. There is thus no consensus as to what this value is. Another possible exploration for this randomness is that this value could be constant for each individual experimental apparatus, and it is not a universal constant.

Zielinski and Villemonte [11] found, using a vortex tank experiment with a free jet as the outlet, that the coefficient of discharge was free from viscous effects at a Reynolds number $V(D/\nu)$ greater than $1x10^3$. Dagget and Keulegan [6] found by using a similar apparatus that the Reynolds number should be greater than $3.2x10^4$ to have a negligible effect on the depth ratio at which an air core vortex would form or not form. Jain et al. [4], using a cylindrical tank apparatus with guide vanes, found that the critical submergence can be calculated (neglecting surface tension effects) from the following equation:

$$K \frac{S_c}{d} = 5.6 \quad N_\Gamma^{0.42} \quad F^{0.50} \tag{5}$$

where $K = f(N_\nu)$ and $N_\Gamma = QS_c/D$, and

$$N_\nu = \frac{Re}{F} = \frac{VD}{\nu} \Big/ \frac{V}{\sqrt{gd}} = \frac{g^{1/2} D^{3/2}}{\nu}$$

K was found to be equal to unity at $N_\nu \geqslant 5x10^4$, which means that at $Vd/\nu \geqslant 5x10^4 \quad V/\sqrt{gd}$ the critical submergence is not a function of the Reynolds number and is therefore free from viscous effects. An interesting result is found for $N_\nu \geqslant 5x10^4$; if the intake velocity, V, is cancelled from this equation, then the minimum diameter, D, recommended to be free from viscous effect is

$$D \geqslant \left(\frac{5x10^4 \nu}{\sqrt{g}} \right)^{2/3} \tag{6}$$

Hebaus [12] showed, using the basic definitions of the parameters used by Jain, that Eq. (5) can be rederived into an explicit equation for the critical submergence S_c . The equation Hebaus found is

$$\frac{S_c}{d} = 19.49\ (N_\Gamma^*)^{.72}\ F^{.86} \qquad (7)$$

where $N_\Gamma^* = \Gamma d/Q$. This equation is free from any implicit dependency on the critical submergence in contrast to Eq. (5) with the term N_Γ.

Using a vortex tank apparatus, Anwar [7] found for a Reynolds number, $R = Q/\nu h$ of greater than or equal to 1,000, viscous effects did not influence the formation of a weak vortex with a narrow air or a deep dimple, where the Reynolds number is defined as $Re = Q/\nu h$; whereas he concludes for a strong vortex with a large air cone that this parameter is very important. In latter experiments, Anwar et al. [13] experimented with a horizontal intake in a flume. From these experiments, Anwar concludes that the flow of a free surface vortex is not affected by viscosity for a Reynolds number $(Q/\nu h)$ greater than $3x10^3$, where h is the depth to the centerline, or the intake. It appears from Anwar's results that the Reynolds number $(Q/\nu h)$ required for an intake to be free from viscous effects in a flume is greater than the Reynolds number required in a cylindrical tank apparatus.

In conclusion, previous research indicates that viscous effects in and around the intake are negligible only if the Reynolds number Vd/ν is greater than or equal to $5x10^4$ and if $Q/\nu h$ is greater than $3x10^3$, whichever is the most conservative of the two relations. These observations may not be accurate if the intake has structural components which will affect the approach flow near the intake.

If Webber number and Reynolds number are dropped from consideration, the dimensional analysis reduces to:

$$\frac{S_c}{D} = f_4 \left[\frac{\Gamma D}{Q}, \frac{V}{\sqrt{gD}}, \frac{\delta_i}{D}\ i=1 \ldots n \right] \qquad (8)$$

B. Design Guidelines

There are an infinite number of configurations by which a closed conduit intake can be constructed. These configurations depend upon the purposes for which the intake is being constructed, as well as the physical configurations of the dam and other factors beyond the control of the designer. A pump intake is usually a vertical inverted bellmouth configuration as shown in Fig. 2. Hydropower intakes normally have either a horizontal or vertical arrangement as schematically given in Fig. 1. The two arrangements presented in Fig. 1 are the configurations on which this study will focus.

The intake design guidelines which are available usually require near perfect flow conditions just upstream of the outlet. Prosser [14] based his design on the diameter of the outlet penstock. His requirements for a horizontal bellmouth are that:

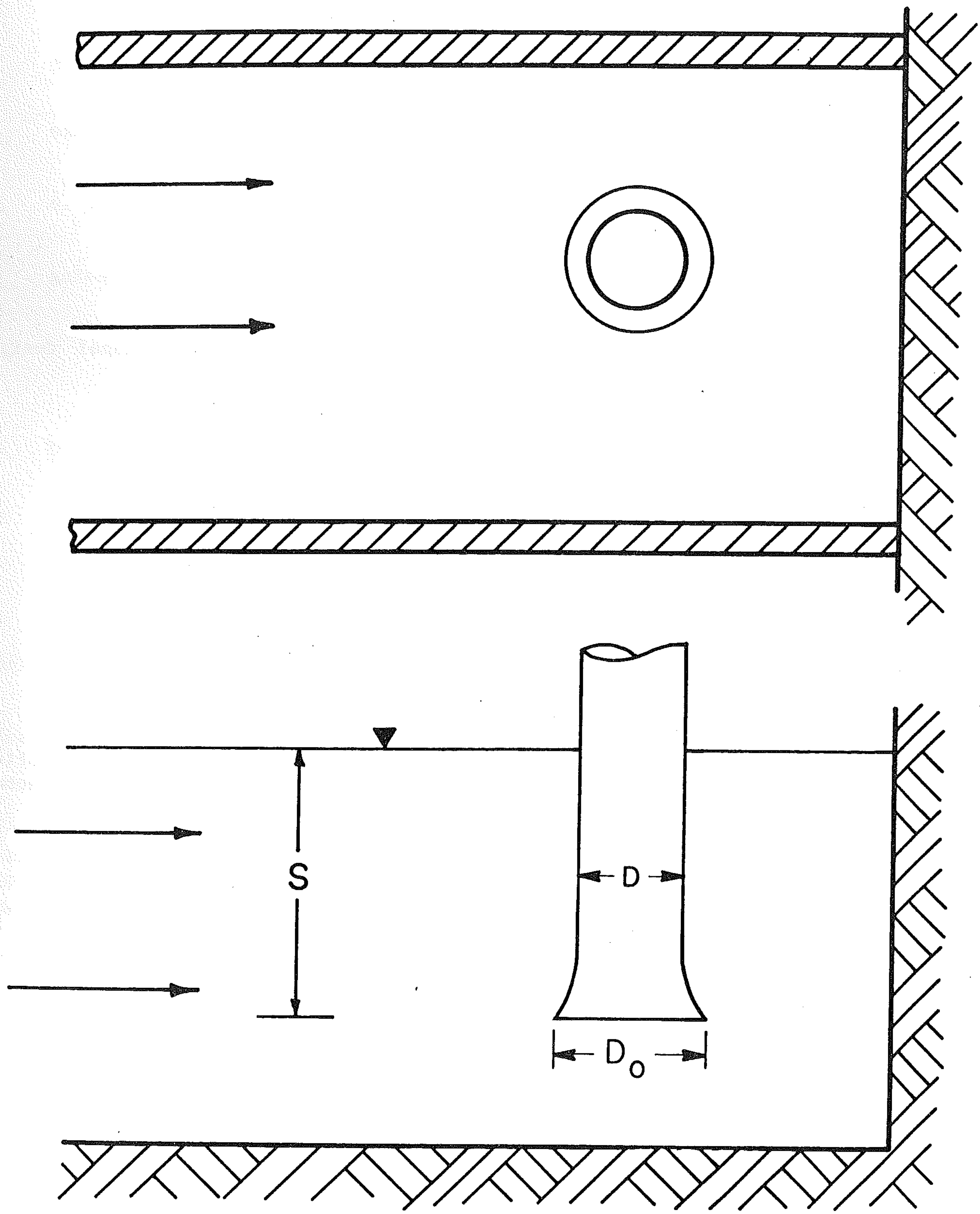


Fig. 2. Vertically inverted intake configuration.

- the upstream flow should be uniform across the channel width,
- supporting pillars should be streamlined to eliminate the possibility of flow separation reaching the intake,
- stagnant flow areas should be filled; for a horizontal intake a vertical face is better than a sloping face,
- average approach channel velocities should be kept below .6 m/s; and
- trashracks should be designed to act as flow straightening vanes.

Prosser further advises on what constitutes a poor channel design upstream of the intake. These factors are:

- abrupt changes in flow directions (e.g. sharp corners or any design which leads to an assymetric distribution of flow,
- rapidly diverging channels,
- a steep slope, and
- blunt support pillars.

These recommendations indicate that there should not be any flow separation upstream of the intake if vortex-free operation is desired.

With this type of approach channel, Prosser recommends an intake submergence of 1.5 D for the horizontal intake. If there is any deviation from the approach channel recommendations previously made, Prosser recommends a hydraulic model investigation.

Gordon [15] has developed design criteria which Montreal Engineering Company of Canada LTD uses to design hydroelectric intakes. With data obtained from 29 existing hydroelectric intakes designed by Montreal Engineering, Gordon developed a graph (Fig. 3) which related submergence to $VD^{1/2}$ where V is the penstock velocity. With this data, Gordon developed envelope curves to describe various regions in the data using:

$$S = CVD^{1/2} \qquad (9)$$

With symmetrical approach flow conditions, Montreal Engineering uses a coefficient C of 0.3 and for lateral approach flow conditions C = 0.4. These coefficients substituted into Eq. (9) describe the lower and upper limits of the envelope in Fig. 3, respectively. One acute disadvantage with Gordon's data is that there are only four installations which experienced vortex problems included in the data. Another major disadvantage is that the parameters are not dimensionless, and cannot be considered a universal relationship for all intake designs.

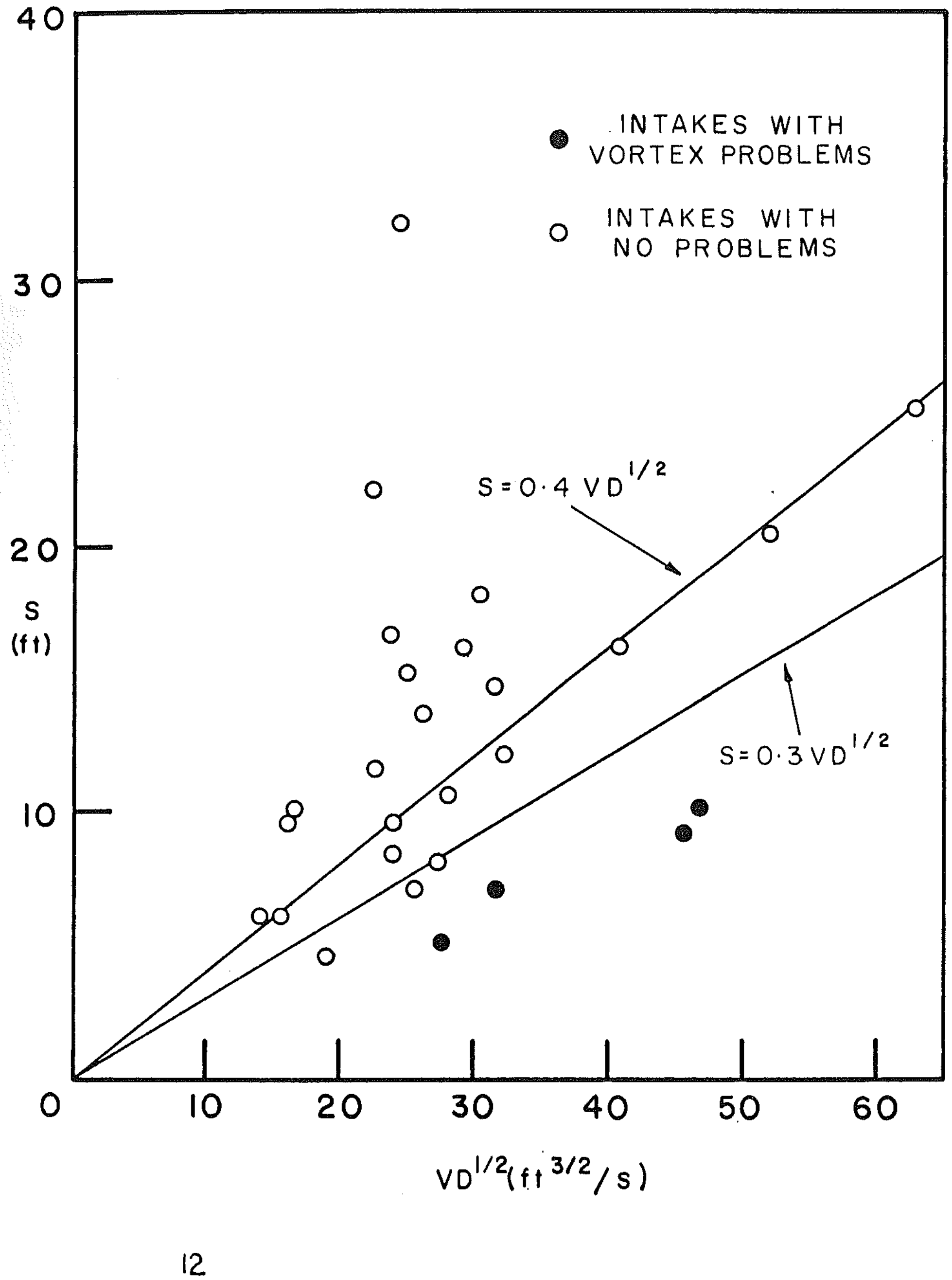


Fig. 3. Gordon's [15] dimensional plot relating submergence to $VD^{1/2}$.

Reddy and Pickford [16] developed a dimensionless graph of S/D vs. $v/\sqrt{gD})$ using Gordon's data as well as other critical submergence data obtained from the literature. Reddy and Pickford's plot indicates that most free surface vortices occurred above the line

$$S/D = F \tag{10}$$

which indicates that the dimensionless critical submergence should always be greater than the Froude number. Furthermore, they found that all the data on critical submergence lies on a band, with the upper band corresponding to

$$S/D = 1 + F \tag{11}$$

and the lower band

$$S/D = F \tag{12}$$

Reddy and Pickford conclude that when vortex prevention devices are used, Eq. (12) will give vortex-free operation. They put one further restriction on Eqs. (11) and (13) by stating that the equations are to be used for inlets where there is no induced swirl caused by artificial boundaries (e.g. the perfect upstream flow conditions previously mentioned). But, in further analyzing Reddy and Pickford's [16] dimensionless plot, it is apparent that they have plotted data for both horizontal and vertically inverted intakes. This implies that the flow field approaching a vertical inverted intake is the same as that for a horizontal intake, and the submergence required for a vertical intake is the same as that required for a horizontal intake. The authors believe that critical submergence for the intake types cannot be equated, since there are great differences in the flow field created by the three types of intakes.

Anwar et al. [13] gives the critical submergence as well as other dimensions for a horizontal intake as a function of the circulation. This requires some knowledge of the circulation prior to the design. Anwar does not give any suggestions on how to calculate this parameter for field conditions.

For a vertical intake without a bellmouth, Humphreys et al. [17] tested a drop inlet entrance to a closed conduit spillway. Some of the results of this study are given in Fig. 4. Humphreys et al. concluded that if the full flow curve intersects the weir curve to the left of the intersection of the weir and vortex envelope curves, no vortex suppression device should be required. However, if the full flow curve intersects the weir curve to the right of the weir and vortex envelope curves, vortex suppression devices should be required. Humphreys et al. used a vortex envelope to postulate that the intake will be free from vortex formation if the submergence ratio, S/D, is greater than the intake Froude number squared.

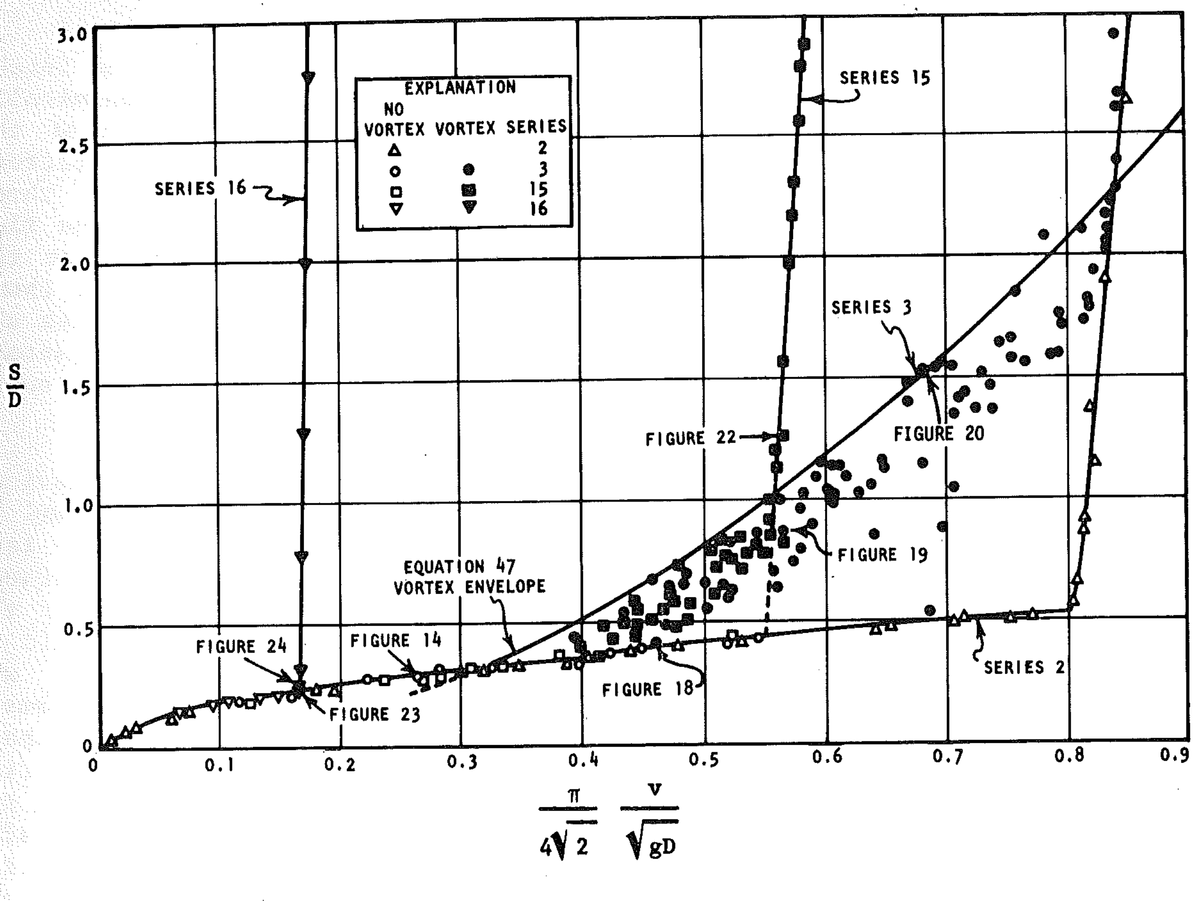


Fig. 4. Dimensionless submergence versus intake Froude number obtained from Humphrey et al. [17].

Recently, Penino and Hecker [18] in a comparison of the experiences that the Alden Research Laboratory had in modeling pumped storage intakes, found no acceptable design standards. Pennino and Hecker also found from their results that maintaining a value of $F = V_o/\sqrt{g\ S_n}$ less than .23, and an S_n/D greater than 0.5 where V_o is the intake velocity at the bellmouth and S_n is the submergence to the centerline, provides a reasonable design guideline. At a higher Froude number, vortex-free operation can be obtained, but a model may have to be constructed to find the more extensive design measures required to keep the intake free of vortices.

In conclusion, despite decades of research in the area of vortex formation, there is very little design information available. Therefore, the only way a designer can currently be certain that a given intake design will be free from vortices is to have a reduced scale hydraulic model test performed.

C. Anti-Vortex Devices

The remedial actions taken once a vortex is discovered at an intake are usually limited to very minor modifications. It may be economically unfeasible or physically impossible to alter the size or depth of the intake, and/or the upstream flow conditions by improving the upstream boundaries. With these limitations, remedies are usually limited to three types of solutions: those which disrupt the angular momentum of the flow such that the formation of a vortex is inhibited, those which force the vortex to try to form in a zone where it is difficult to form, or those which increase the area of the outlet such that the intake velocities are decreased. None of these solutions destroys the angular momentum upstream of the intake, and thus there still may remain a large amount of swirl entering the intake that is hazardous to the turbines or pumps.

Denny and Young [19] listed several types of anti-vortex devices available. These and other devices are shown in Figs. 5, 6, 7, and 8. One of the most popular and inexpensive remedies, as shown in Fig. 5 is a floating raft which disrupts the angular momentum at the water surface. Ziegler [20] found the water surface is not the optimum location for the raft. He noted that swirling motion remained below the floating raft in his model, whereas by submerging the raft, this swirling motion was removed. Furthermore, Ziegler found the optimum depth to be only a small distance below the water surface. The optimum depth is that depth where the submerged raft is able to provide resistance to the swirling motion above the raft as well as below the raft. If the depth of the raft is too great, the raft is unable to supply resistance to the swirl above the raft. This swirl then set up a vortex, and because of the higher velocities closer to the outlet, the vortex is stretched and a high velocity inner core of a small radius is formed.

Trashracks which also disrupt the angular momentum of the flow have been effective as vortex suppressors in some instances [1, 20, 21]. Ziegler [20] modeled trashracks by using different sizes of screen. He found vortex formation at these screens to be dependent on the size of screen, and therefore dependent on the resistive action of the screen. Ziegler felt the results obtained with screens to represent the trashracks

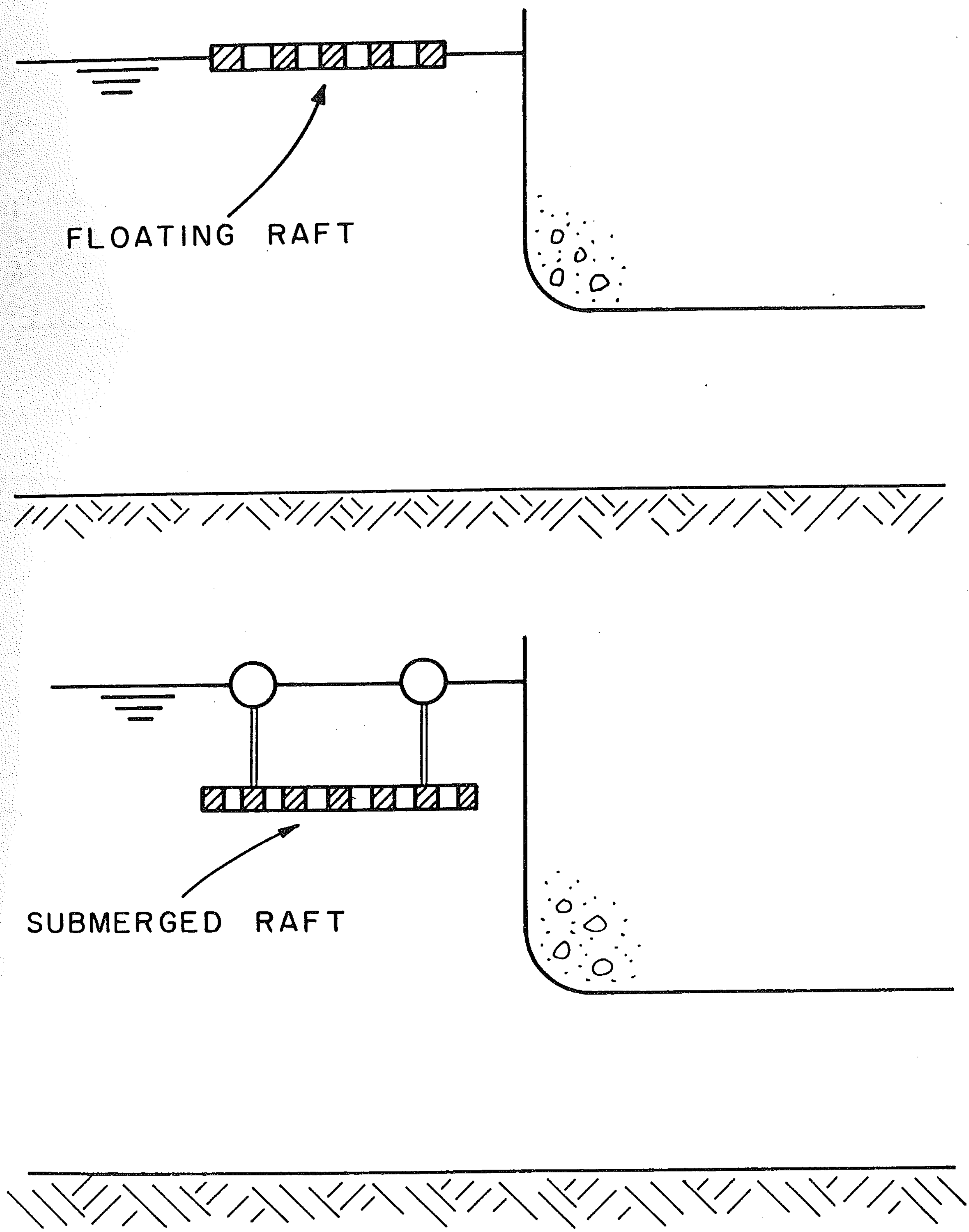


Fig. 5. Floating and submerged raft vortex suppressors.

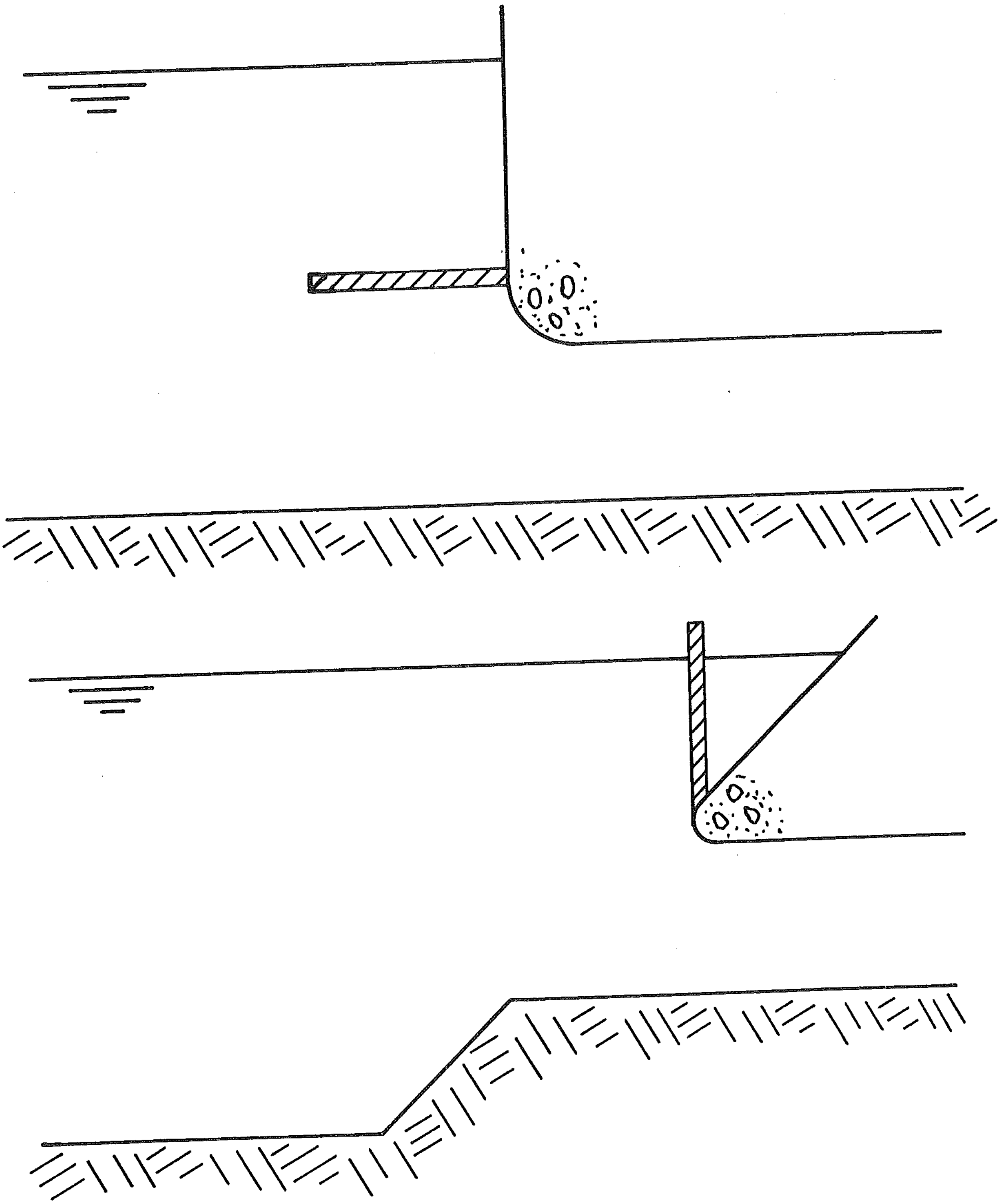
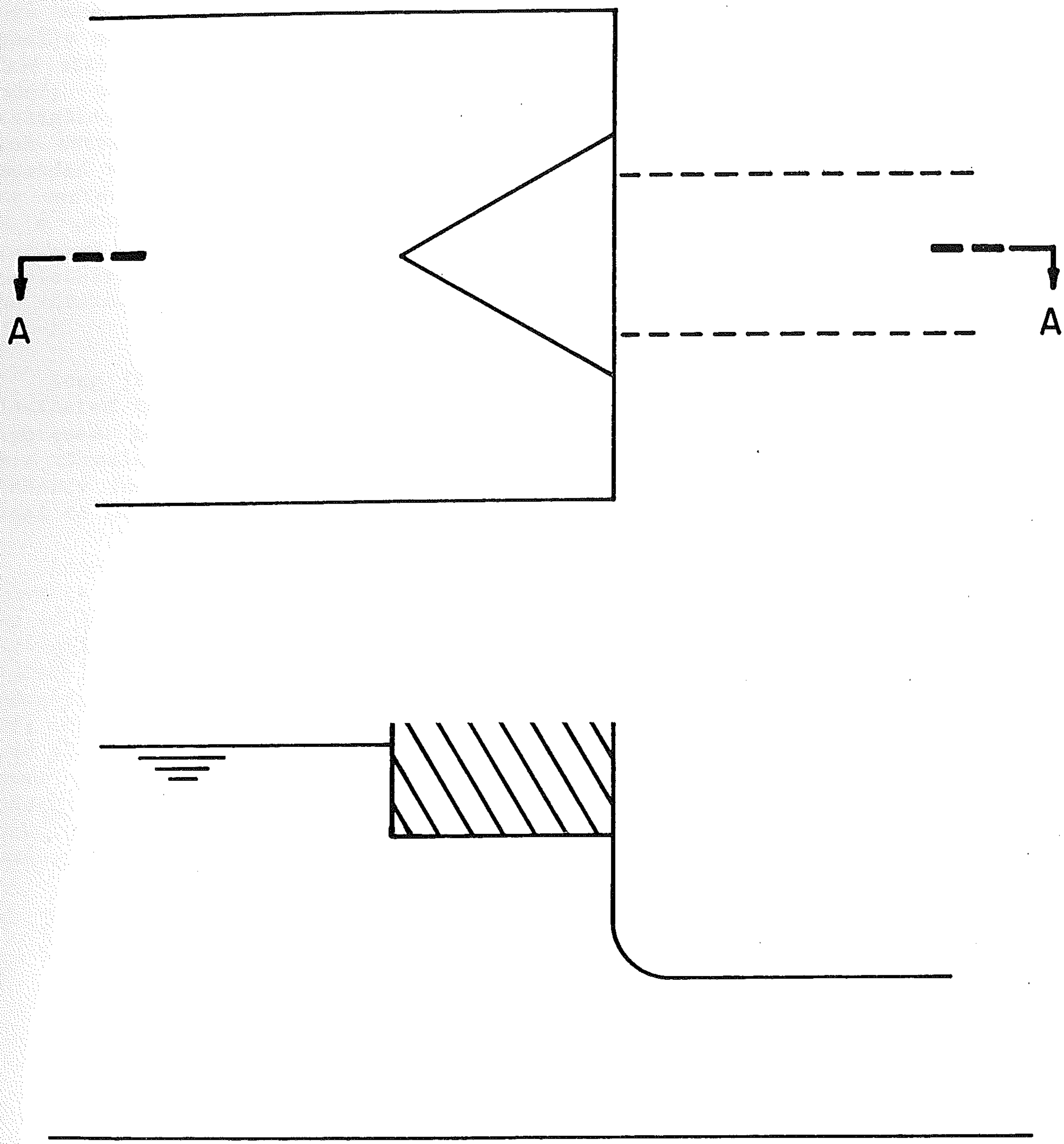


Fig. 6. Extended plates used to dissipate vortices (Blaisdell [21]; Denney and Young [19]).



SECTION AA

Fig. 7. Wedge type vortex suppressor (Song [23]).

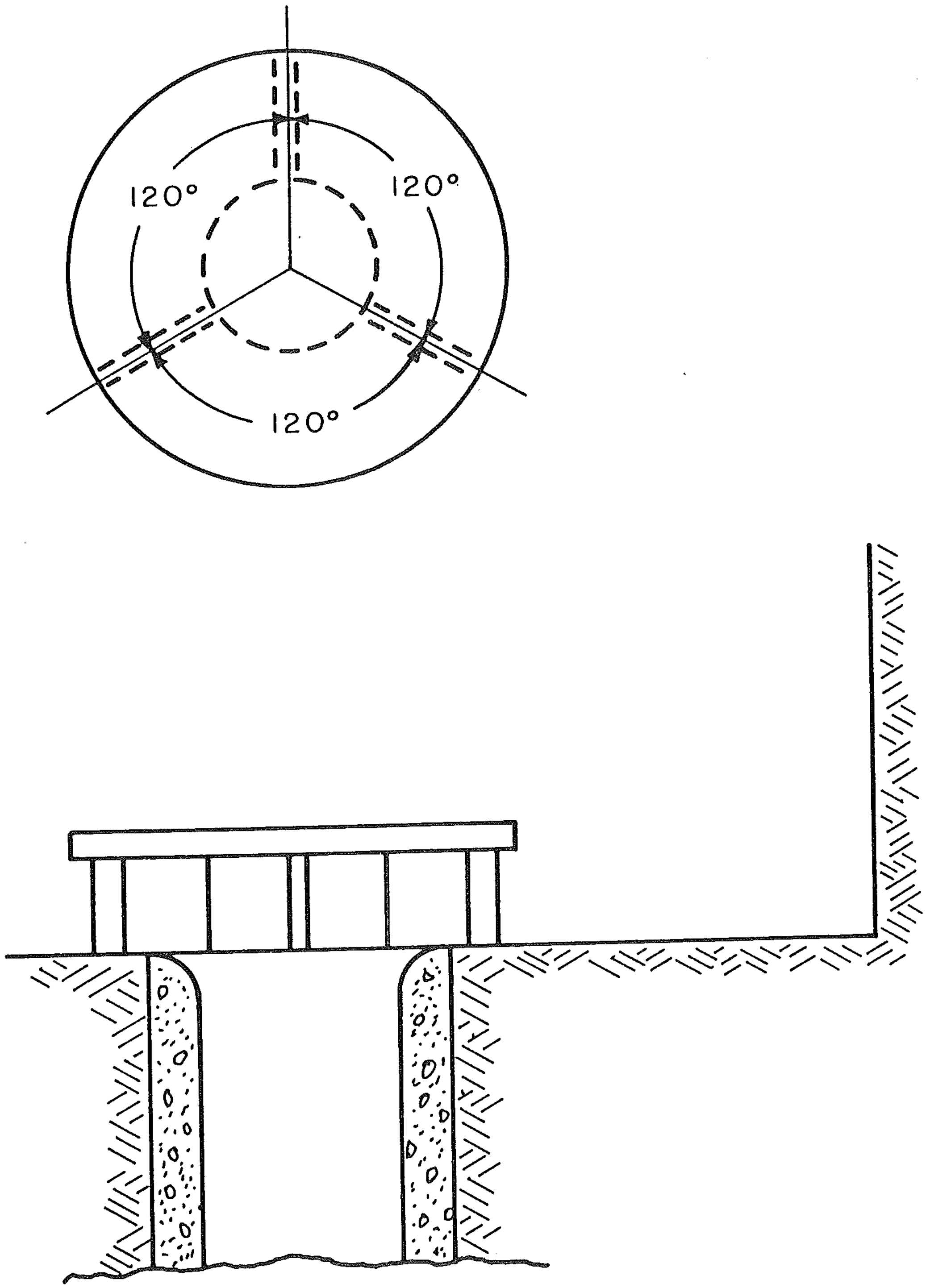


Fig. 8. Covered intake type vortex suppressor (Blaisdell [2]; Humphreys et al. [17].

were conservative in comparison to the prototype. Prototype trashracks are usually made out of rectangular bars which can be thought of as limited flow straightening vanes, whereas screens are cylindrical wires in the model, or cylindrical bars in the prototype, and are poor flow straightening vanes. Thus, the prototype trashracks would straighten the flow better than the model. Ables [1] used a scaled bar trashrack of expanded width as a vortex suppressor in his model to reduce the tendency for vortex formation. Gwinn [22] found that using a steel deck grating in a prototype closed conduit spillway for small watershed projects decreased the strength of the vortex, but did not dissipate the vortex completely. Ziegler [20] confirmed Gwinns' results with screens placed at the intake. A vortex formed and did not dissipate as it passed through the screen.

Song [23] developed a vertical wedge shaped anti-vortex device which dissipated the angular momentum very well. It was not necessary for the suppressor to interfere with the flow into the intake but simply to dissipate circulation near the surface. In addition, Song concluded that the tendency for vortex formation is diminished if the plan of the approach canal to the intake is less like a circle.

Another vortex suppressor which is common in small intakes such as culverts is the hooded inlet shown in Fig. 6 which essentially extends the top of the intake. The Agricultural Research Service has spent many years developing inexpensive intakes for Soil Conservation Service projects. Blaisdell [21] found good results in vortex suppression for culverts by extending a circular plate above the intake (hooded inlet) Humphreys et al. [17] and Blaisdell [21] also found good results by placing a circular cover over the drop inlet to a closed conduit spillway (shown in Fig. 8). This cover essentially increases the cross-sectional area of the intake, reducing the entering velocities, and forcing the flow through a contorted path, thus reducing large-scale circulation. The cover is also a source of headloss, and not often used in hydroelectric intakes.

III. ANALYSIS OF VORTEX PROBLEMS ENCOUNTERED AT EXISTING INSTALLATIONS

The majority of the research on avoiding free-surface vortices at intake structures has been performed on individual installations primarily through model studies. The experience associated with these structures may be valuable in developing general rules-of-thumb for intake design. As discussed in Section II, Gordon [15] and Pennino and Hecker [18] have previously compiled prototype and model data for this purpose. This section is an extension of those analyses to incorporate additional intake installations and to further refine the analysis of previous experience.

A. Case Studies

There are many factors which contribute to free-surface vortices at intakes, as indicated by Eq. (8). The most important parameters are the dimensionless submergence, S/D, intake Froude No., $V/\sqrt{gD}$ or $V/\sqrt{gS}$, and the large-scale circulation in the flow approaching the intake. The circulation parameter is dependent upon many factors in the approach conditions which are entirely site specific. The primary source of circulation is the angular momentum induced by the geometric arrangement of the intake approach, such as flow separation around the leading edge of a wall, channel irregularities, or a prevailing stream flow pattern. Any generic guidelines, therefore, run into this basic problem; the circulation of the flow near the intake is site-specific because the approach flow conditions in each installation are unique. Unfortunately, approach circulation appears to be as important or even more important than dimensionless submergence and intake Froude No. in the occurrence of vortices at an intake. The importance of circulation will be apparent in the following case studies.

1. Lower St. Anthony Falls Lock and Dam

The lower St. Anthony Falls Lock, given in Fig. 9, has a severe vortex which forms when filling the lock chamber. The vortex is so severe that it is hazardous to small craft, as tragically demonstrated in 1974 when a lock employee in a small boat was accidentally drawn into the vortex and killed. This vortex problem provides an excellent case study because the U. S. Army Corps of Engineers Waterways Experiment Station (WES) performed a hydraulic model study in order to determine how to minimize the intensity of the vortex. The required alterations to the lock were found to be extensive and could not be economically justified. This illustrates a frequent occurrence--that solving a vortex problem after a structure has been built is usually extremely expensive.

The intakes to the lock-filling culvert system are square vertical bellmouths as shown in Fig. 10. During filling, 25 percent of the flow entered through intake #1, 22 percent through #2, 23.5 percent through #3, and 29.5 percent through #4.

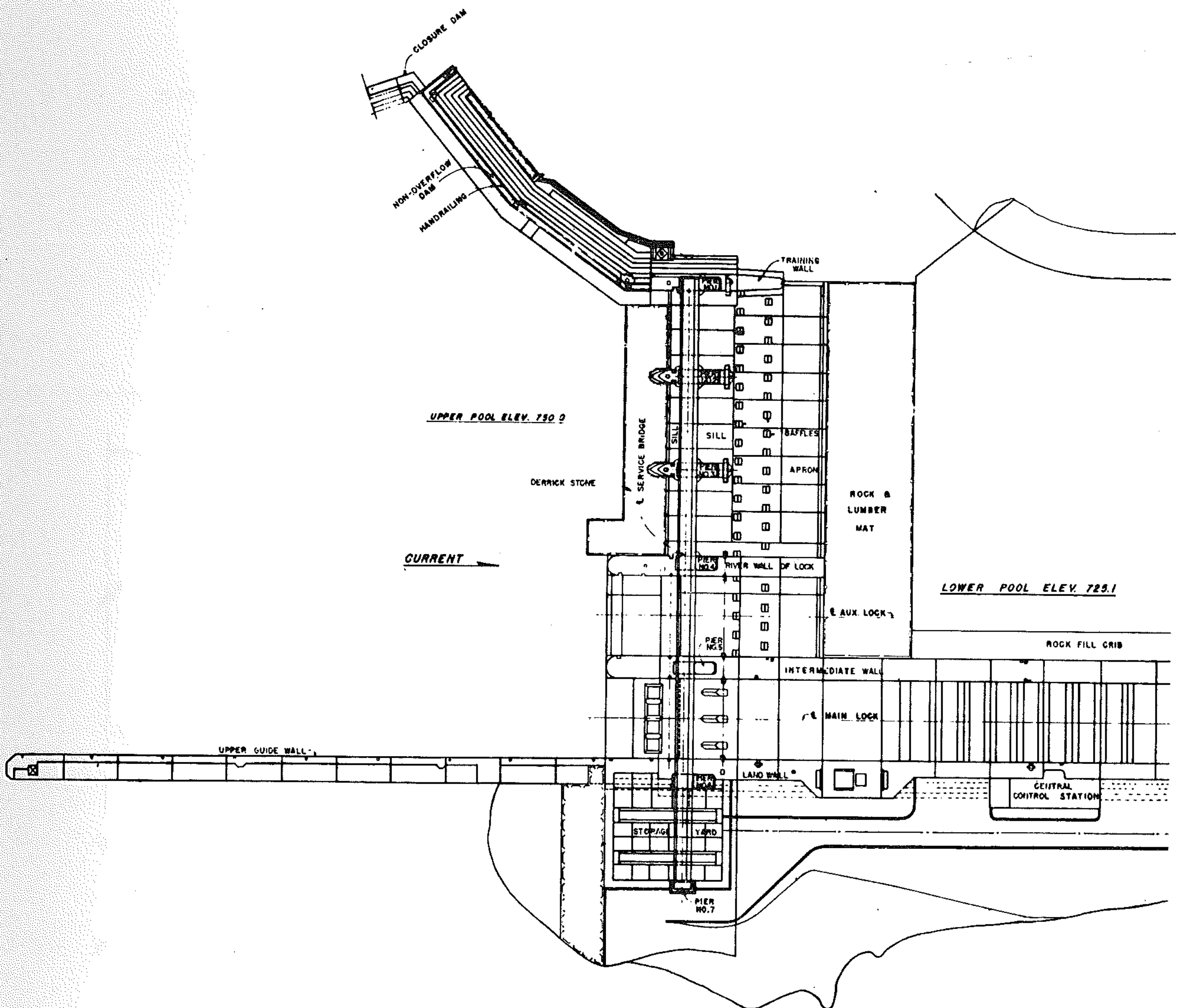
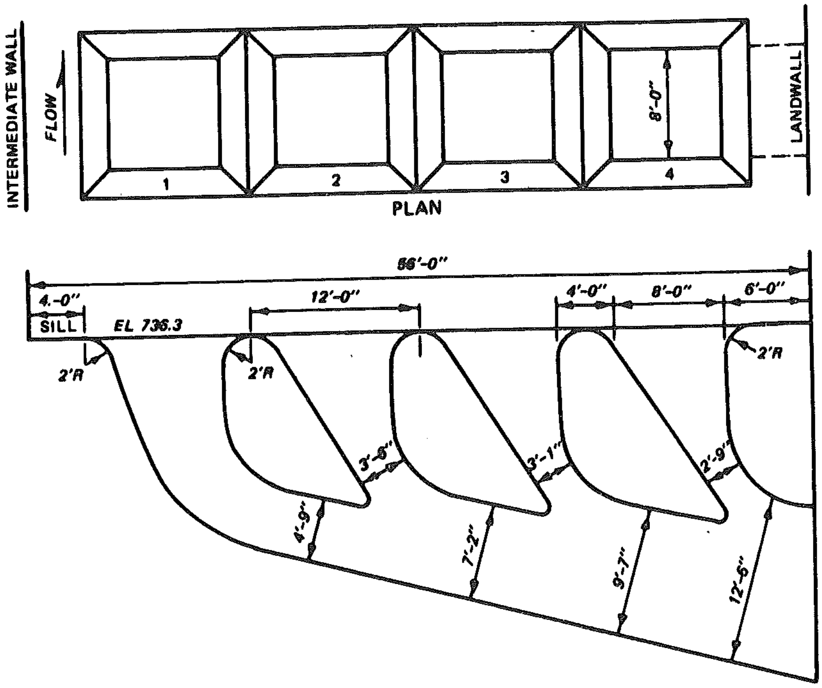
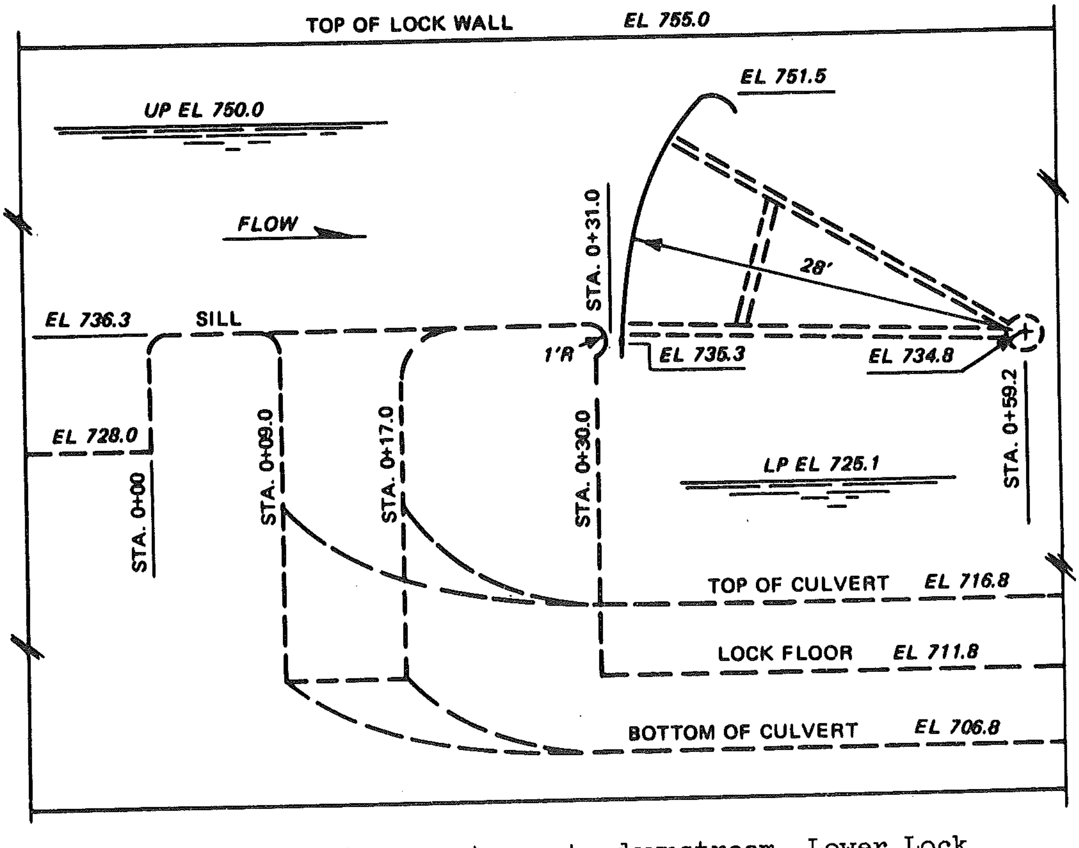


Fig. 9. Plan of the Lower St. Anthony Falls Lock and Dam [1].



a. Cross section, sill intake manifold, Lower Lock



b. Cross section, upstream to downstream, Lower Lock

Fig. 10. Details of existing intakes at the Lower St. Anthony Falls Lock and Dam, taken from Ables [1].

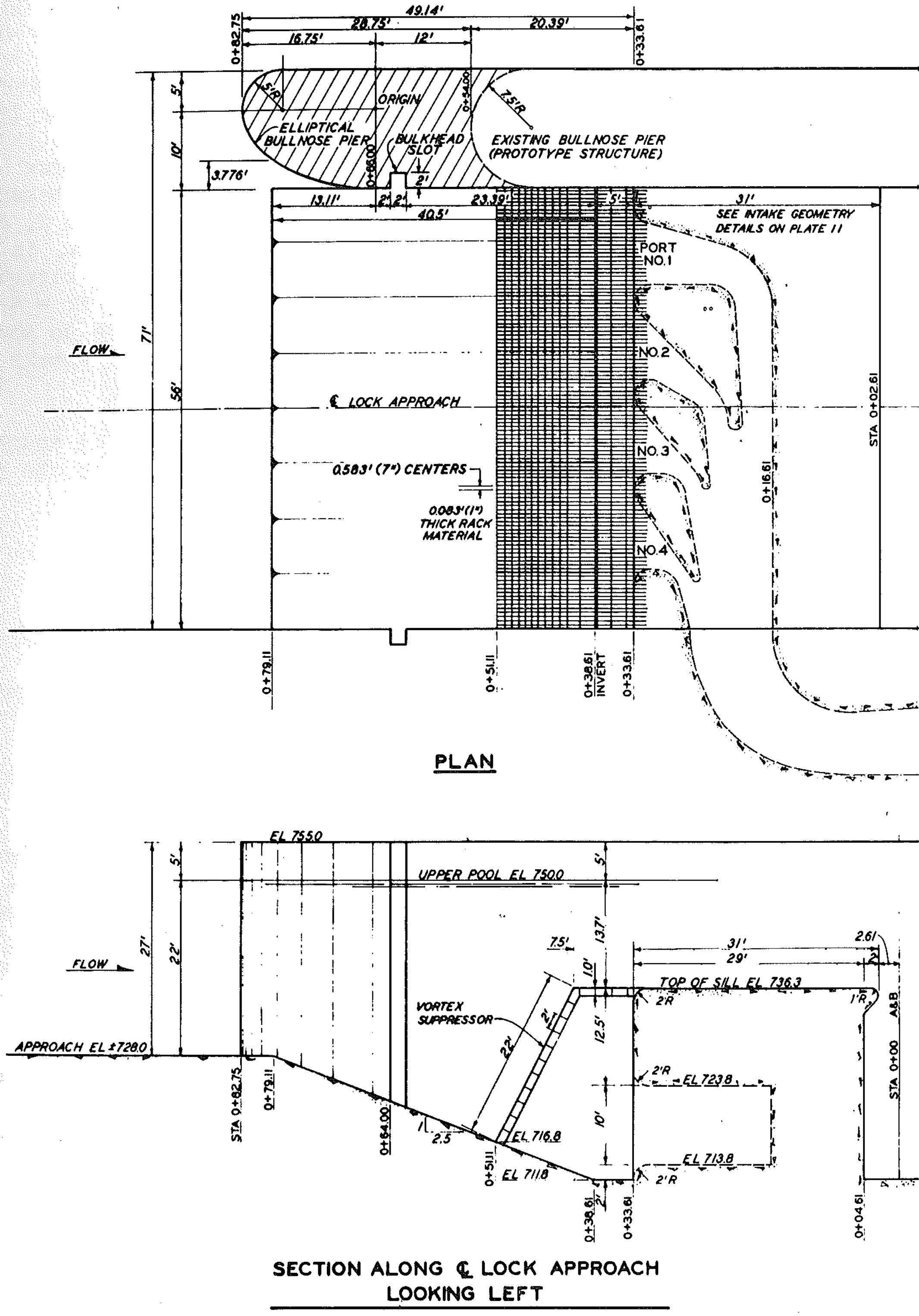


Fig. 11. Recommended intake design to prevent vortex formation at the Lower St. Anthony Falls Lock and Dam, taken from Ables [1].

A field survey was undertaken on May 17, 1983, to examine the approach conditions to the four intakes. The lock staff were kind enough to operate the intake at design flow (which they rarely do because of the vortex) to facilitate the survey. It was immediately apparent that the primary cause of the vortex is a common one--separation around the leading edge of the canal wall, known as a bullnose pier. Once the intake valve is opened, water from the impoundment flows past the bullnose pier at 90 degrees. The flow separates around the leading edge of the pier because of the high velocities and large angle of attack, as shown in Photos 2, 3, and 4. This separation induces an adverse pressure gradient which, in turn, causes backflow along the wall. The backflow creates the circulation required for the vortex to form in intake #1, at S/D = 3.0 and $Fr = V/\sqrt{gD} = 0.89$. As time progresses the rotation of the first vortex sets up the circulation required for a second, less severe vortex to form in intake #4 at S/D = 2.85 and Fr = 0.80.

The hydraulic model study subsequently performed at WES [1] found that the vortex could be eliminated with the following alterations to the intake design:

- Rebuild the intake to a horizontal, rather than vertical arrangement.
- Increase the submergence of the intake from 13.7 to 26.2 ft.
- Add a vortex suppressor, straightening vanes which would also serve as trash racks.
- Extend the bullnose pier 28-3/4 ft further upstream with an elliptical, rather than a circular, shape.

In other words, build an entirely new and more expensive intake structure. The WES study found that less drastic measures simply would not work. The final design suggested by the WES study is given in Fig. 11. These four recommendations identify the two important parameters in avoiding free-surface vortices: a large submergence and approach flow with a minimum amount of large-scale circulation.

It is interesting to note that an early model study of the lock system performed by staff from the U. S. Corps of Engineers at the St. Anthony Falls Hydraulic Laboratory found no vortex problems at the intake. The only difference between the two model studies is that the early one did not adequately model the approach conditions, and the separation around the bullnose pier was not as severe.

2. Mayfield Hydroplant Expansion

The Mayfield Hydroelectric Power Facility experienced vortices and very turbulent flow in the forebay area to the intakes of the downstream power tunnel, a diversion facility. A high velocity flow leaves the power tunnel and separates as it expands and distributes to the four plant intakes. The separation was caused by the large angle of incidence in the expansion wall, directing a jet at the two center intakes, and causing a

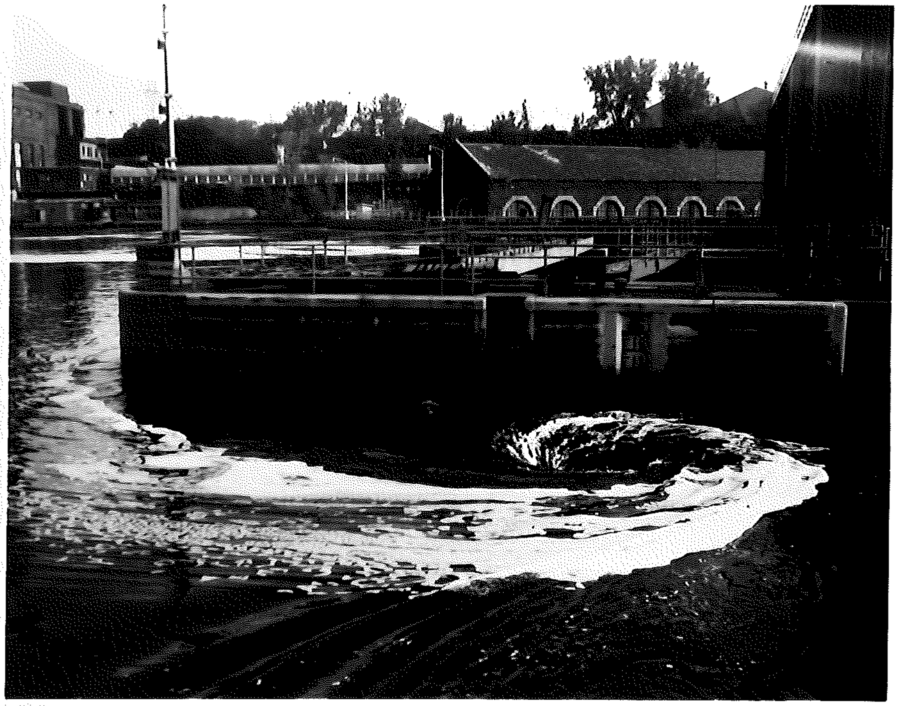


Photo 2. View showing vortex in conjunction with the front bullnose pier at intake No. 1, Lower St. Anthony Falls Lock and Dam.

Photo 3. Separation past the bullnose pier F ≅ .89, S/D = 3.0

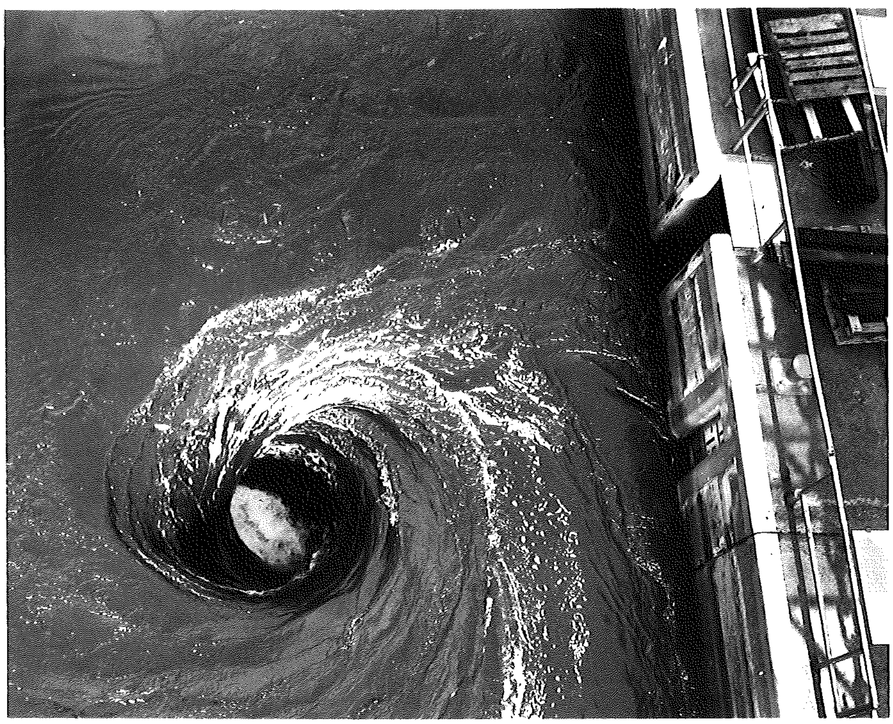


Photo 4. Another view of the vortex. Note size of vortex in comparison to the pallet on the pier. F = 1.15, S/D = 3.0.

flow across the two outer intakes. This was evidenced by the existence of large shock waves at the pier noses, which caused uneven water surface elevation at the intakes. A model study was performed by Song [23] at the St. Anthony Falls Hydraulic Laboratory to correct this problem.

It appeared that free surface vortices were induced by the eddies, formed by the flow separation and drawn into the intake. Submerged guidevanes improved the flow distribution, but did not entirely eliminate surface swirl. The addition of a vertical wedge over the intake finally broke down the surface swirl. Song attributed the effectiveness of the vertical wedge to the extremely noncircular geometry which resulted in the intake bays. It should be noted that this intake had a very low submergence, as compared to other intakes with similar velocities, S/D = 0.6 and Fr = 0.57.

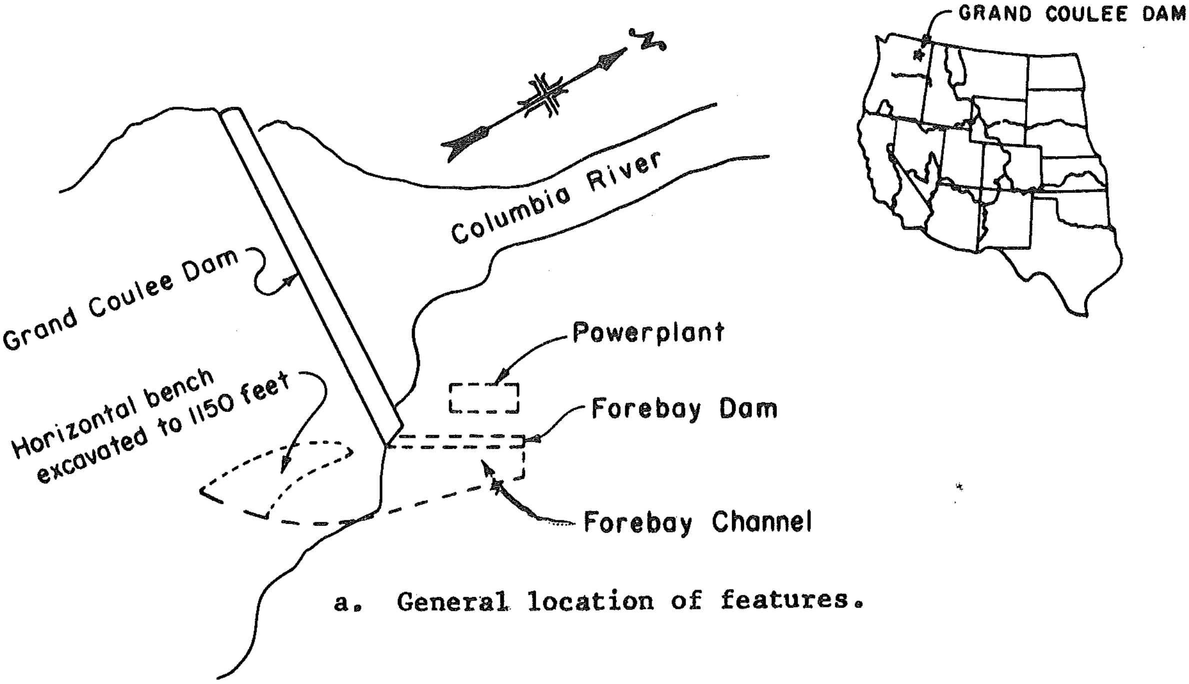
3. Grand Coulee Third Power Plant

Another project where free-surface vortices are associated with separating flow was the hydraulic model study for the Grand Coulee Third Power Plant given in Figs. 12 and 13 (S/D = 1.23 and Fr = 0.77). In this study a continuous air entraining vortex formed which was dissipated by adding a flow straightening trash rack to the front of the intake structure. Then, instead of a continuous air entraining vortex, a dye core vortex was observed in the model at increased model intake velocities.

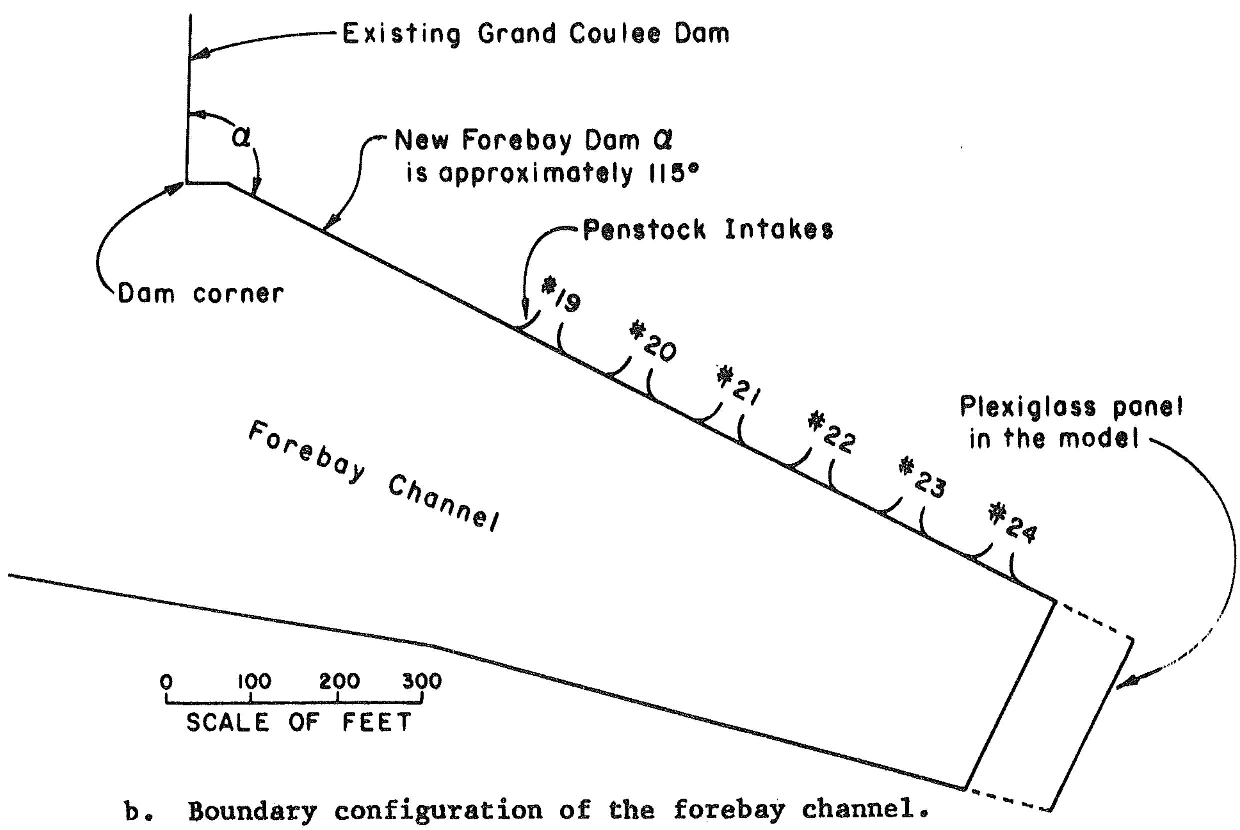
In the model study Ziegler [20] examined the effect of the separation past the corner leading into the supply canal. He placed an elliptical shaped guidewall in the model to suppress the separation of surface flow currents past the corner shown in Fig. 12. In this case, it is interesting that although surface streamline patterns were separating, the dye streaklines below the surface were not separating as the flow went into the intake supply canal. Ziegler found a decrease in vortex severity when the guidewall was used. Without a guidewall, an air entraining vortex with a continuous air core readily formed and entered intake No. 19. With the guidewall, vortex severity was reduced to where only small bubbles occasionally pulled off the vortex tail and entered the intake. This separation was not the primary cause of the vortex formation, but it was a major factor. The other factors in this case were the submergence, the intake velocity, and that the flow was required to turn 90° in order to enter an intake. This poor intake canal configuration as well as the upstream flow separation brought about the vortex problems described in the model study.

4. Three Swedish Intakes

A classical discussion of flow problems at Swedish intakes was the study by Lenhart Rahm in 1953 [3]. The study primarily dealt with the effect of various intake designs on the intake velocity whether favorable or unfavorable to plant operation. In so doing, Rahm analyzed the impact of upstream velocity distribution on vortex formation. He found that a leading parameter in the formation of vortices was the flow separation past some obstacle, be it horizontal or vertical. Untra Power Plant on the Dalalven River, shown in Fig. 14, was the first intake investigated. Rahm found the formation of a vortex street which was a consequence of flow separation past the discontinuity where the lined banks are suspended by



a. General location of features.



b. Boundary configuration of the forebay channel.

Fig. 12. Overall location sketch and location of intakes for Grand Coulee Third Power Plant, taken from Ziegler [20].

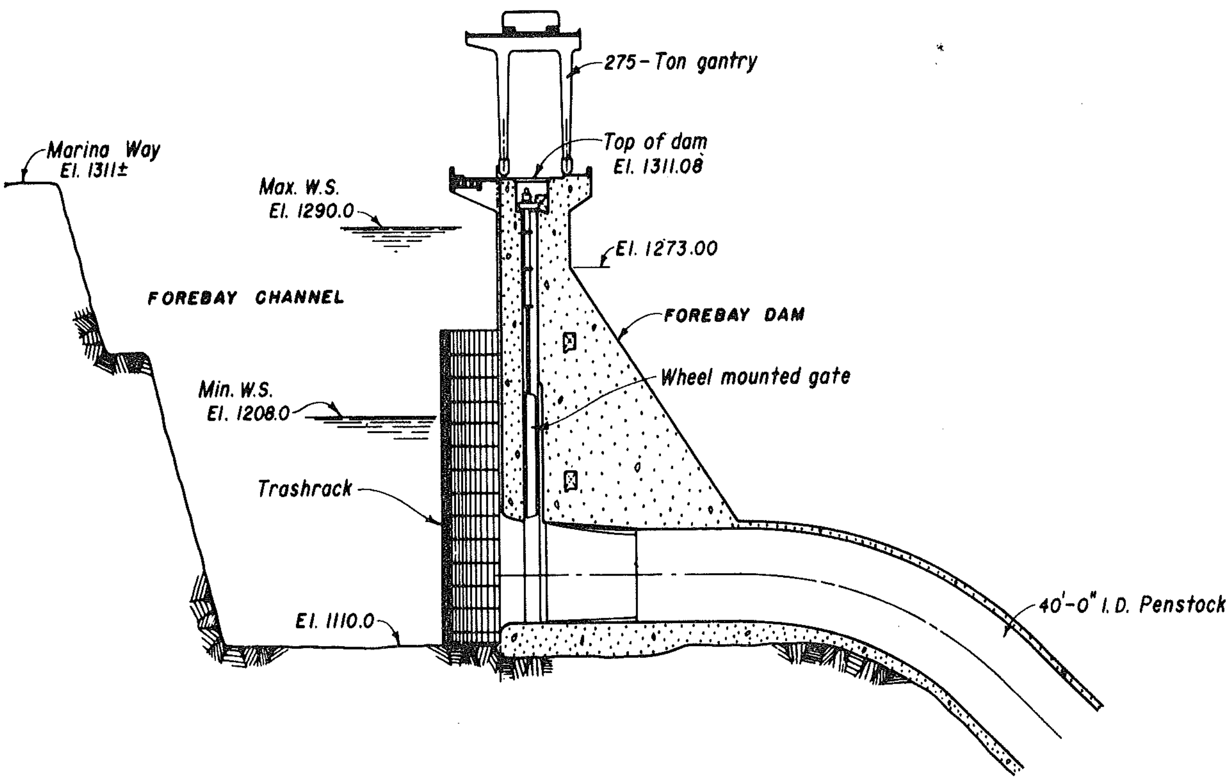


Fig. 13. Typical section view through forebay dam and penstock of Grand Coulee Third Power Plant, taken from Ziegler [20].

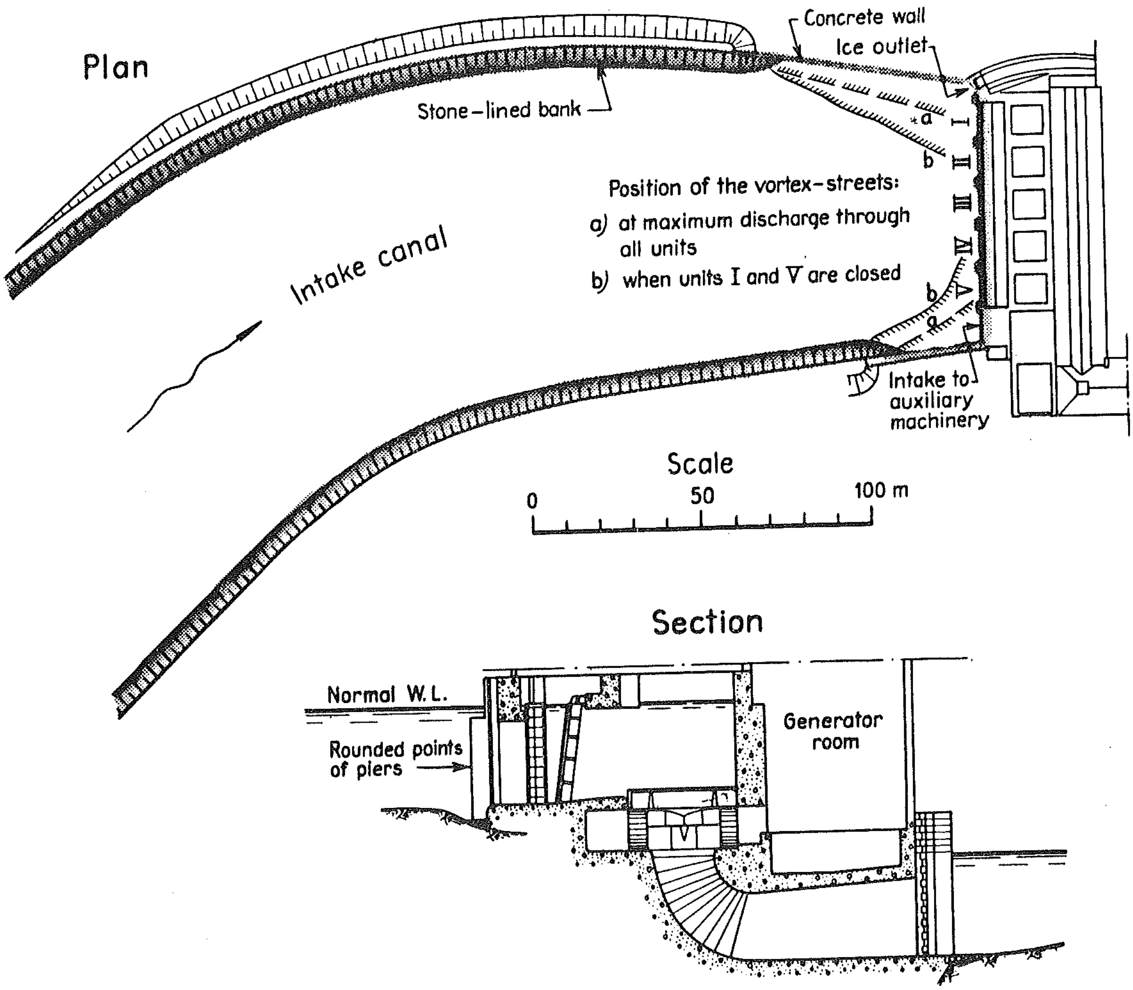


Fig. 14. Untra Power Plant plan and section, taken from Rahm [3].

concrete walls. Rahm also found that vortex formation was enhanced by the piers on the intake structure, which were rounded only part of the way to the water surface. At high flows and the corresponding higher headwater elevation, flow separation around the edge of the sharp edged portion of the piers formed a coherent eddy in the stop log recesses, where air suction first formed.

A similar situation occurred at the Åtorp Power Plant on the Letälven River, shown in Fig. 15. The pull of the intake created a surface current over the top of the submerged intake canal walls, perpendicular to the main stream, as shown in Fig. 16. This flow pattern formed an upwelling region (bulb) inside the canal wall which was the source of a large, stable eddy, and ultimately a free-surface vortex at intake I.

Finally, Rahm discusses the Hammarforsen Power Plant on the River Indalsälven, shown on Fig. 17. The approach flow velocities from upstream are very slow at approximately 0.5 m/sec. Rahm found, however, that

> "Owing to the positions of the units and the dam, the flow to the intakes was very oblique, and at various combinations of discharge the direction of velocity deviated at least 30 - 45° from the perpendicular to the front of the intakes. As a result, strong local vortexes in the lee of the intake piers were formed, in spite of the evenly distributed and relatively low velocity. The vortexes in front of intakes I and II were strong enough to suck down with ease large pieces of wood, but could, however, be prevented by means of floating wooden grids."

In conclusion, all of the intake case studies indicate the importance of a straight and uniform flow upstream of the intake to prevent vortex formation. The same could be said for virtually every intake with vortex problems. An ideal approach condition, however, is rarely possible, and intake designers must accept a compromise dictated by the specific conditions of the site. There are currently very limited design guidelines to assess the potential for vortices at a given intake. In the next section, field and model experience at existing installations is compiled to give some very general guidelines which may be combined with a qualitative assessment at a given site. In a later portion of this report more specific design criteria are developed for a specific type of intake.

B. Analysis of Vortex Activity at Existing Intakes

The case studies discussed in the previous section reveal the important parameters in vortex formation: circulation in the flow field approaching the intake, intake submergence, and the intake velocity or the intake Froude number. The analysis of this section will attempt to develop general rule-of-thumb guidelines for critical submergence from the experience of existing installations. Parameters generally known for an intake will be used, such as submergence, intake diameter, and intake velocity. The approach circulation is an important parameter which is not known for existing intakes and will be ignored. This analysis will

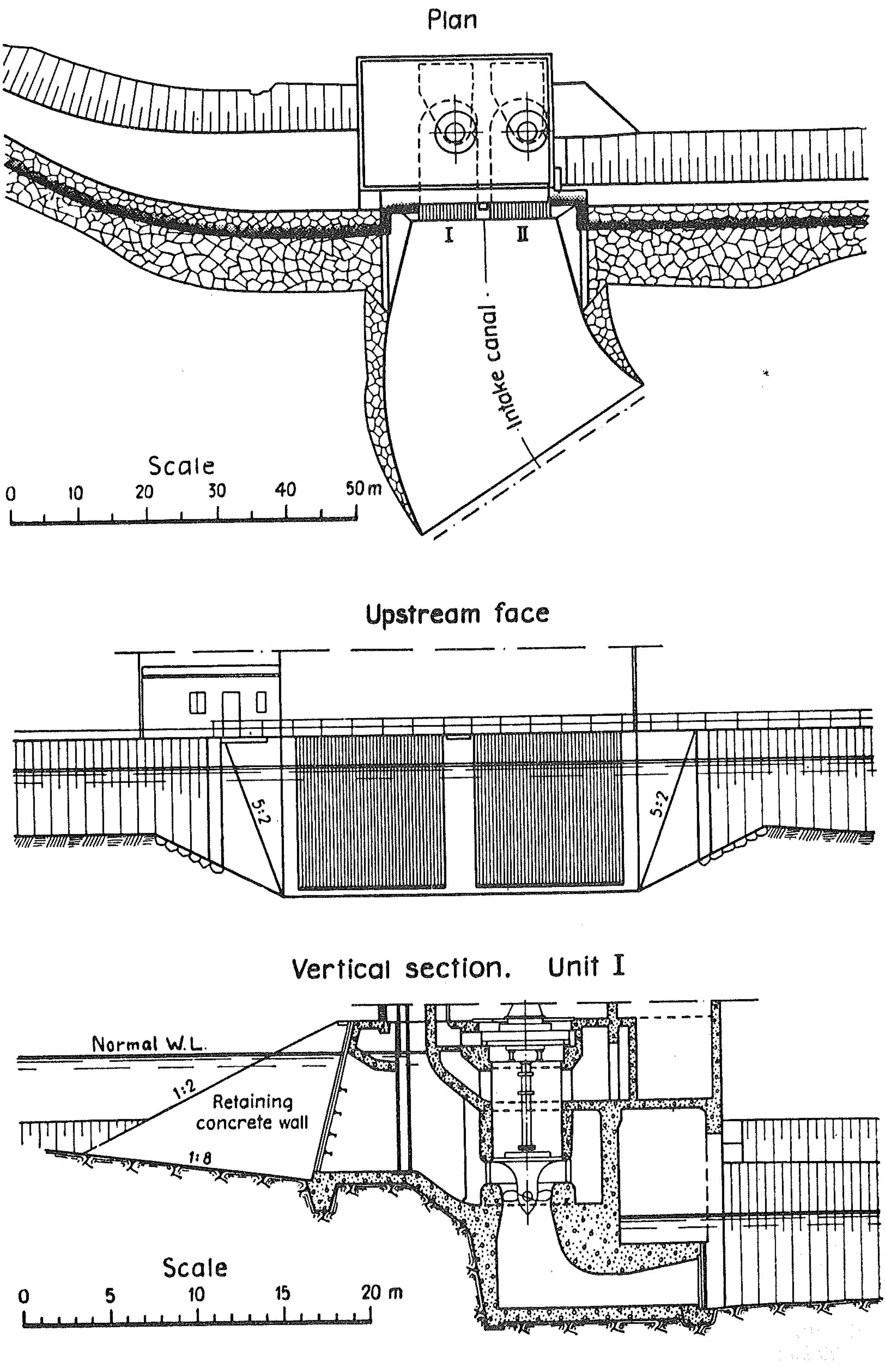


Fig. 15. Åtorp Power Plant plan upstream face, and vertical section of unit I, taken from Rahm [3].

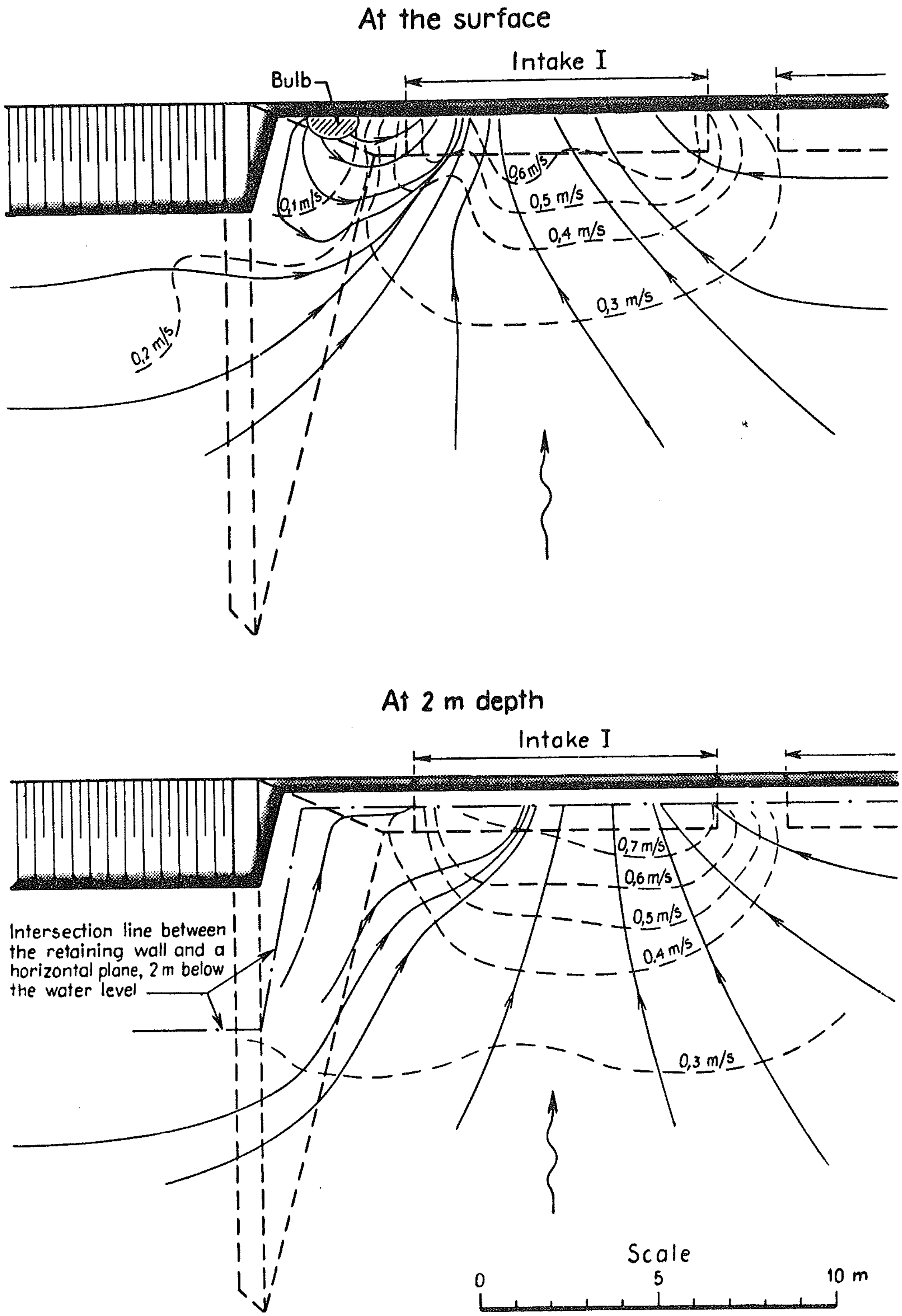


Fig. 16. Åtorp Power Plant streamlines and velocities in front of intake I with a discharge of 37 m^3/s, unit II being closed, taken from Rahm [3].

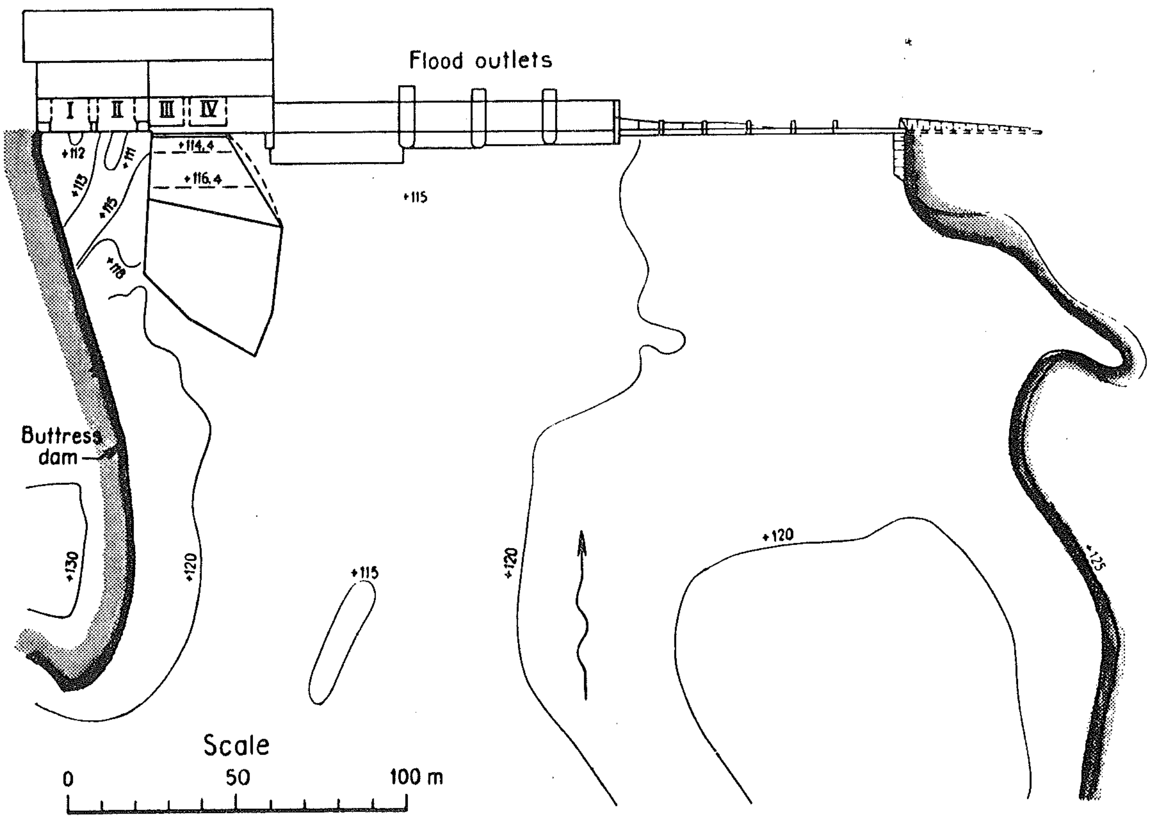


Fig. 17. Hammarforsen Power Plant plan of the river upstream of the intakes, taken from Rahm [3].

therefore approach the problem from the same point of view as an intake designer, who has little or no knowledge of the approach circulation. A conclusion often drawn is that a submergence exists which is deep enough such that vortex formation will not occur, even with the worst possible circulation of the intake approach flow. In order to determine what this submergence is, existing and model intake submergence and discharge data were collected and analyzed.

The starting point in this analysis was to obtain the data used by Gordon [15] to develop his dimensional relationship. This related the submergence, S, and $VD^{1/2}$ as previously shown in Fig. 11. The data were made dimensionless using the dimensionless submergence, S/D and the intake Froude Number $V/\sqrt{gD}$. On plotting this data a surprising result was obtained. The submergence data for the intakes which had vortex problems lay about the line $S/D = 1.15\ V/\sqrt{gD}$; this result was very encouraging, but after further data on similar intakes was plotted, the initial result was found to be erroneous.

Besides Gordon's data, Hecker [24] Pennino and Hecker [18] list several other existing installations which have experienced vortex related difficulties. These installations are both prototype intakes as well as model intakes. The information which is tabulated in these results is very sketchy; thus, an attempt was made to either obtain prototype information from the dam owner or obtain the results of a model investigation. This was done in order to obtain the most accurate values of submergence and discharge available. In addition to these sets of data, information on intakes with and without vortex problems known to the authors were included in the analysis. Thus, although the analysis is similar to Gordon [15] and Pennino and Hecker [18], the data set used is the most comprehensive to date and will provide an improved basis for intake design.

Clarification of the definition of the submergence and the diameter, D , is needed to avoid confusion. The literature review mentions several different submergences which are currently in use. Initially the submergence was defined as shown in Fig. 2, but it was found necessary to redefine the submergence for intakes of the form shown in Fig. 18. The submergence will be defined as the distance from the water surface to the point of intersection of the soffit bellmouth with a line drawn perpendicular to the water surface on the top of the bottom bellmouth lip, as drawn in Fig. 18. The diameter will be defined as being the minimum diameter to which the bellmouth narrows, as is also shown in Fig. 18.

The data on existing installations and model studies of proposed installations were compiled and are presented in Fig. 19. Sources of the data are given in Table 1. Also given in Fig. 19 are two envelope curves which result from Gordon's [15] criteria. $C = 0.03$ corresponds to $S/D = 1.7\ F$, and $C = 0.4$ corresponds to $S/D = 2.27\ F$. It is immediately apparent that neither Gordon's nor Reddy and Pickford's [16] design criteria are sufficient to avoid vortex problems. In fact, Fig. 2 confirms Penino and Hecker's observation that there is virtually no submergence at which an intake designer can be certain of vortex-free operation.

There is a region, however, in Fig. 19 where free-surface vortices are less likely to occur; that is the region segmented by a dimensionless

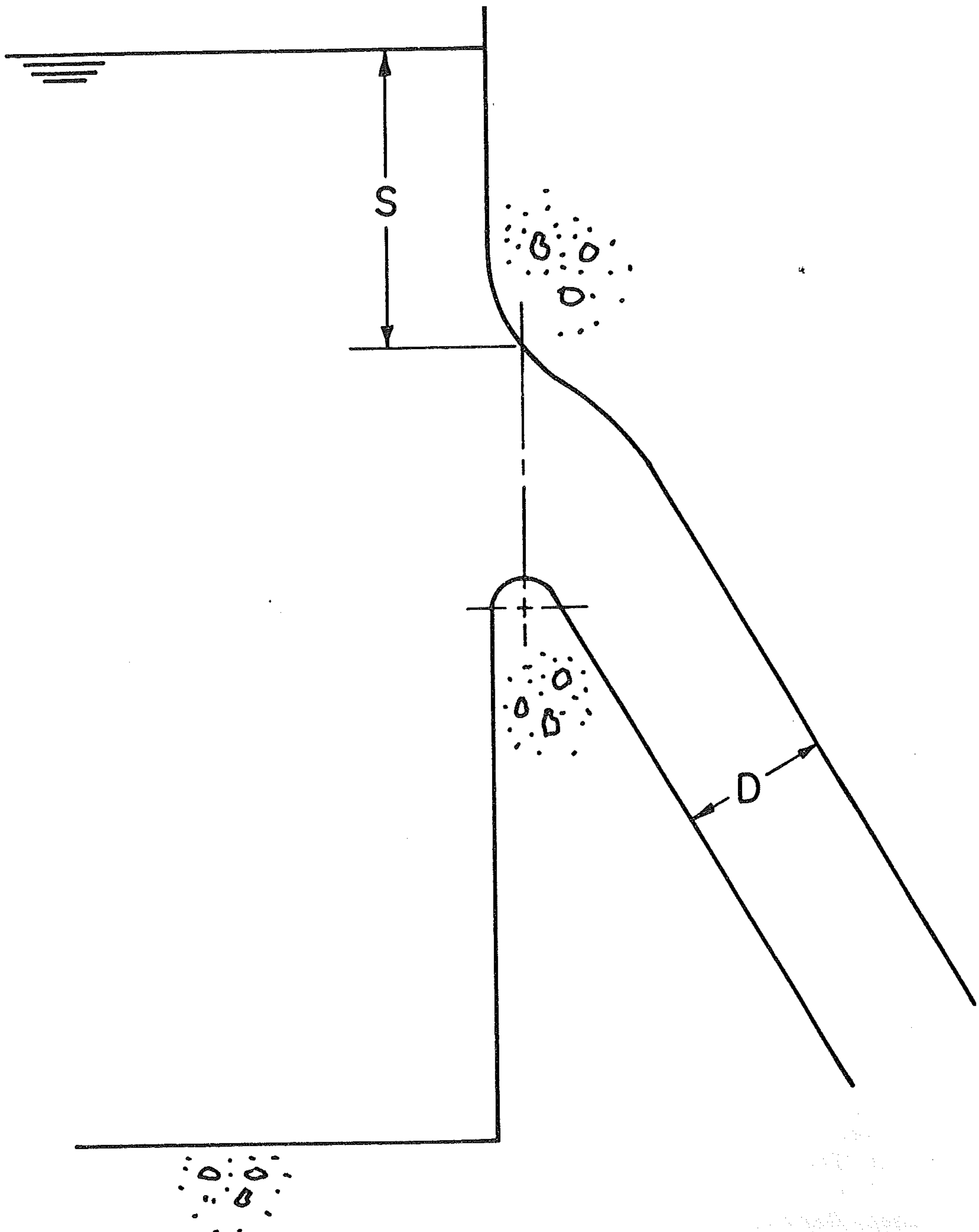


Fig. 18. Definition sketch used to describe submergence, S, and diameter, D, of a horizontal intake.

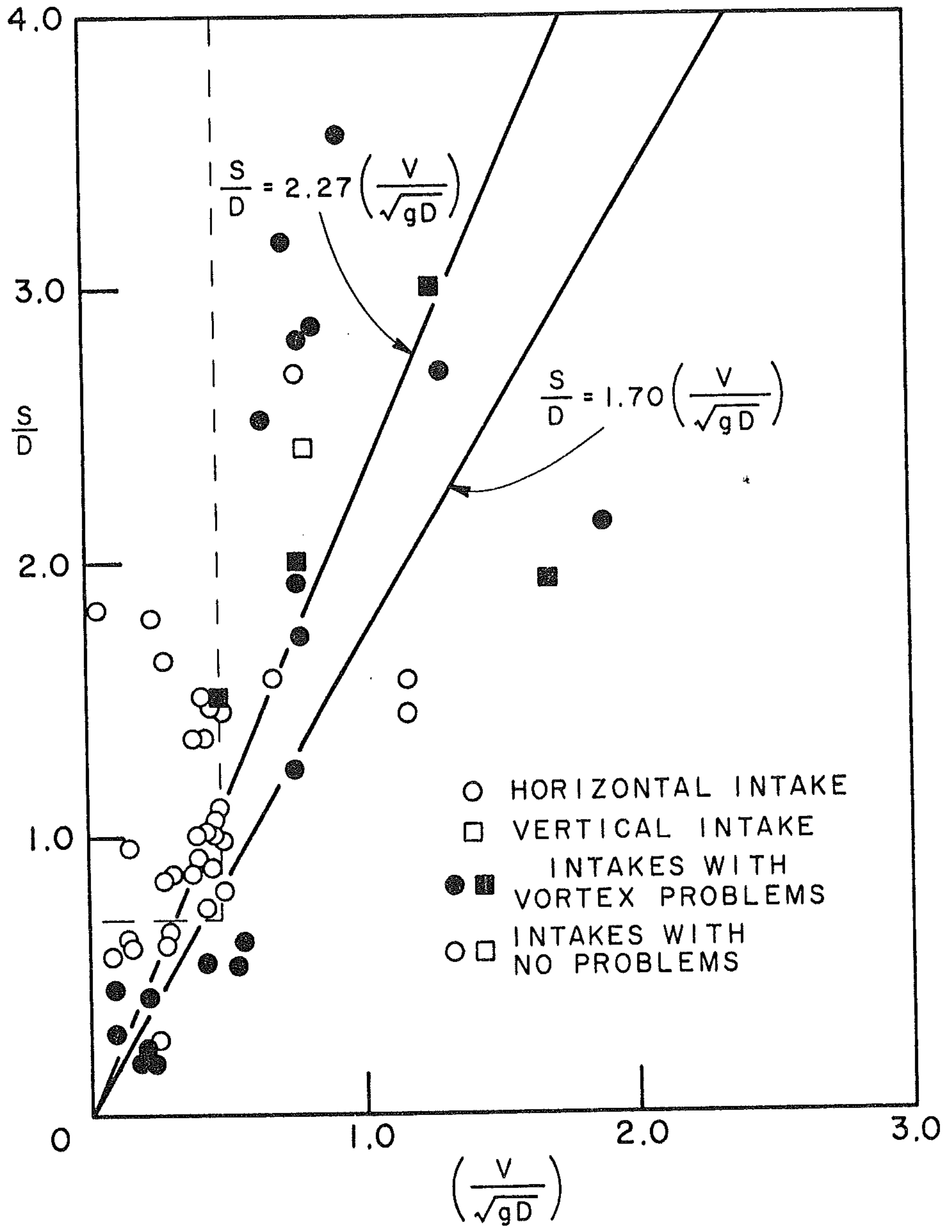


Fig. 19. Dimensionless plot of data obtained from existing intakes, field installations and model studies.

TABLE 1. List of Data and Source's Used for Fig. II-1.

Experienced Vortex Formation	S/D	F	Type of Intake	Project	Source of Information
N	1.78	.24	Horizontal	Snare (1)	[15]
N	1.45	.47	Horizontal	Rundle (1)	[15]
N	6.09	.47	Horizontal	Three Sisters	[15]
N	.59	.17	Horizontal	Brochet	[15]
N	.56	.42	Horizontal	Cape Broyle	[15]
Y	.23	.22	Horizontal	Jim Grey	[15]
N	1.36	.40	Horizontal	Mayo	[15]
N	1.36	.41	Horizontal	Horsechops	[15]
N	.63	.16	Horizontal	Bearspaw	[15]
N	.85	.32	Horizontal	Menihek (1)	[15]
N	1.00	.41	Horizontal	Rio Bueno	[15]
N	.98	.50	Horizontal	Interlakes	[15]
N	.73	.44	Horizontal	Pocaterra	[15]
N	.60	.28	Horizontal	Chute Wilson	[15]
Y	.54	.43	Horizontal	Smelter	[15]
N	1.63	.29	Horizontal	White Horse	[15]
N	.86	.39	Horizontal	Moggotty	[15]
N	1.44	.50	Horizontal	Rattling Brook	[15]
N	.92	.42	Horizontal	Hart Jaune	[15]
N	1.50	.45	Horizontal	Rundle(2)	[15]
N	.84	.29	Horizontal	Snare (2)	[15]
N	.78	.50	Horizontal	Spray (2)	[15]
N	.64	.30	Horizontal	Waterloo Lake	[15]
N	1.43	1.18	Horizontal	Rattling Brook	[15]
N	1.00	.45	Horizontal	Taltson	[15]
N	1.06	.47	Horizontal	Sandy Brook	[15]
N	1.09	.48	Horizontal	Brazeau #1	[15]
N	1.00	.47	Horizontal	Brazeau #2	[15]
Y	2.13	1.90	Horizontal	Chururaqui	[24]
Y	2.41	.80	Vertical	Bad Creek	[24]
Y	2-4	.79	Vertical	Bear Swamp Pumped Storage	[24]
N	1.82	.06	Horizontal	Effestinag	[24]
N	.96	.16	Horizontal	Foyers Pumped Storage	[24]
N	.56 - 3.06	.09	Horizontal	Kariba Hydro Project	[24]
N	.53	.55	Horizontal	Ludington Pumped Storage	[24]
Y	2.86	.85	Horizontal	Orville Dam Diversion	[28]
Y	3.57	.95	Horizontal	Orville Dam Diversion	[28]
Y	4.29	1.04	Horizontal	Orville Dam Diversion	[28]
Y	2.52	.65	Horizontal	Taum Sauk	[24]
Y	2.69	1.32	Horizontal	Enid Dam	[24]
Y	1.72	.79	Horizontal	Nimbus Dam Power Intake	[24]
Y	1.93	1.69	Vertical	Shadehill Dame Flood	[24]
Y	1.23	.77	Horizontal	Grand Coulee Third Power Plant	[20]
Y	.57	.78	Horizontal	Glen Canyon Dam	[27]
NM	.89	.46	Horizontal	Havasu Pumping Plant	[30]
NM	1.56	1.18	Horizontal	Grand Coulee Pumping	[29]
N	1.93	.78	Horizontal	Glen Canyon Dam	[27]
Y	.601	.57	Horizontal	Mayfield	[23]
Y	3.00	1.27	Vertical	Low St. Anthony Falls Lock and Dam	[1]
Y	0.18	0.20	Horizontal	Untra Power Plant (all Intakes but I)	[2]
Y	0.18	0.24	Horizontal	Untra Power Plant (at Intake I)	[2]
Y	0.18	0.23	Horizontal	Atorp Power Plant	[2]
N	0.26	0.26	Horizontal	Alfta Power Plant	[2]
Y	0.42	0.22	Horizontal	Hammarforsen Power Plant (Intakes I & II)	[2]
Y	0.28	0.10	Horizontal	Hammarforsen Power Plant (Intakes III & IV	[2]
Y	1.48	.47	Vertical	Rapidan Power Plant	In progress at SAFHL

submergence, S/D, greater than 0.7 and an intake Froude number, $V/\sqrt{gD}$, less than 0.5. If a given intake installation has extremely poor approach conditions, such as a short headrace wall, or an intake in the middle of a large pool, vortices are still possible in this "safe" region. For a small hydroplant (e.g. less than 2 MW), in this relatively safe region with good approach conditions, it may be cost-effective to forego an intake model study. Consultation should always be obtained, however, from individuals with expertise in intake vortices. What looks like good approach conditions to the designer may have a deceptive source of approach circulation.

One interesting aspect of Fig. 19 is that there is no "safe" dimensionless submergence for intakes with an intake Froude number greater than 0.5. There are, however, intakes in this region without vortex problems. The reason, of course, is approach circulation, the ignored parameter in this analysis. Intakes with a very good approach flow, such that there is little large-scale circulation entering the intake, can operate without free-surface vortices at a high intake Froude number. On the other hand, intakes with a poor approach flow can have free-surface vortices at intake Froude numbers as low as 0.5, and possibly lower. In this region, a model study must currently be recommended under all circumstances. Improved design criteria, which will hopefully be developed from more generic experimental investigations in the future, may reduce the prevalent need for intake model studies.

In order to refine some of the guidelines which may be extracted from Fig. 19, an experimental investigation of intake vortices was undertaken and will be described in Section IV. The study was limited to vertical bellmouth intakes in a headrace canal, and is only the beginning of the work required to develop comprehensive guidelines.

IV. EXPERIMENTAL STUDY ON VERTICAL BELLMOUTH INTAKES

A. Experimental Facility

1. Design Objectives

The primary objective of the experimental flume design was to simulate conditions common in vertical intake installations. Most intakes have a headrace (approach) canal, and are located an equidistance from the walls at the end of the flume. For this reason, false walls were installed in the flume to simulate headrace canals of various lengths and widths.

Another important consideration in simulating field installations is the angle of approach flow into the canal. The literature review emphasizes the importance of circulation in vortex formation. Flow entering the canal at an angle will have a given amount of circulation which can increase the tendency for free surface vortices. Guide vanes were therefore installed at the head of the canal to control and predetermine the angle of approach to the headrace canal.

There were also three hydraulic design objectives for the flume. The first objective was to have a uniform velocity profile upstream of the intake. The second objective was to size the outlet so that viscous forces would not restrict vortex formation which might complicate scaling of the results. The third objective was to have adequate inflow and outflow so that data could be taken over the desired range of inlet Froude numbers.

The first objective is important because of the role vorticity plays on the amount of circulation present in the flume. The effect of approach flow circulation on vortex formation is a primary objective of this study. Approach flow circulation, therefore, was a parameter to be controlled in the experiments; and "background" circulation such as that caused by a non-uniform velocity profile needed to be maintained at a low level.

Viscous effects do not normally impede free surface vortex formation in field installations. Thus, it is imperative that viscous effects be negligible in model intakes as well in order to scale up the results with confidence. This has been found to be true for intakes with an intake Reynolds number greater than $5x10^4$ $V/\sqrt{gD}$, Jain [4], as previously mentioned in the literature review. Thus, for a given kinematic viscosity and intake throat velocity, the throat diameter of the intake should be

$$D^{3/2} \geqslant 5x10^4 \frac{\nu}{\sqrt{g}} \tag{13}$$

where V = intake throat velocity. A throat diameter of 6 inches was chosen to give no viscous effects on free surface vortices. Daggett and Keulegan's

[6] criteria of $Re = VD/\nu \leq 3.2 \times 10^4$ indicates that viscous effects will occur at $V \leq 0.68$ ft/sec, or at $F = V/\sqrt{gD} \leq 0.17$. Thus, the possibility of viscous effects at low intake Froude numbers must be kept in mind.

To satisfy the third objective, a range of intake Froude numbers up to 2.0 was desired. This was accomplished with sufficiently large inflow and outflow pipe to allow a discharge of 1.6 ft^3/sec. The physical arrangement will be described in the next section.

2. Description of Test Apparatus

The test apparatus was a wooden flume with a bellmouth outlet given in Photo 5 and Figs. 20, 21, and 22 and is located on the main shop floor of the Laboratory, next to a 24-inch flume. The 24-inch flume required a catwalk for visual observations. This catwalk, shown in Photo 5, was used for visual observations of the surface flow in the flume.

The wooden flume, supported by 2"x6" planks and concrete blocks, consists of a stilling basin, a transition section, and a test section, as shown in Fig. 20. Flow was supplied from the Mississippi River in a once-through mode with an 8-inch supply line which ran from the main supply channel to the stilling basin. Inflow was measured with an orifice meter calibrated in-line and connected to a manometer with either mercury or Meriam blue as indicator fluids. The stilling basin was designed to produce a fairly straight uniform flow out of this section. This was achieved with an 8-inch lateral diffuser pipe shown in Figs. 20 and 21 with 2 inch diameter holes drilled to stagger at +45° and -20° off horizontal, and directed at the rear wall. The flow was further smoothed by flowing through a 6 inch thick rock crib, which consisted of rocks coarser than a 3/4 inch sieve. Finally, a transition zone of 7 ft was used to dampen any large scale eddies.

Visual observation was made possible by installation of a 4'x8'x3/4" plexiglass sidewall and a 4'x56"x3/4" plexiglass wall at the end of the flume.

The interior components of the test section were the movable intake canal walls and the bellmouth. The bellmouth was centered 16 inches from the rear wall and 16 inches from the side wall as shown in Figs. 20 and 21. The intake canal walls consisted of a 52 x 48 inch rear wall, and canal side walls which were variable in length. The variable length canal side walls were produced using four 1/2" plexiglass panels, 48" deep, for each canal wall. The length of the panels were 1/2 ft, 1 ft (two sets) and 4 ft, which provided for large variation in length. The length of the canal side walls used in the experiment were the 3 ft, 6 ft, and 9-1/2 ft long combinations. The 6 ft combination is illustrated in Fig. 20 and 21.

The guide vanes were located 4-1/4 inches upstream of the movable side walls, shown in Fig. 20. These vanes consisted of 11 sheet metal vanes, 8-1/2 inches in length with a spacing of 4-1/2 inches. Each vane had a 90° lip bent on the top and bottom. A pivot was obtained by drilling a hole through the lip and placing a metal peg and washer through the hole. This simple mechanism made examining the consequence of changing the approach flow angle relatively easy between ± 45°.

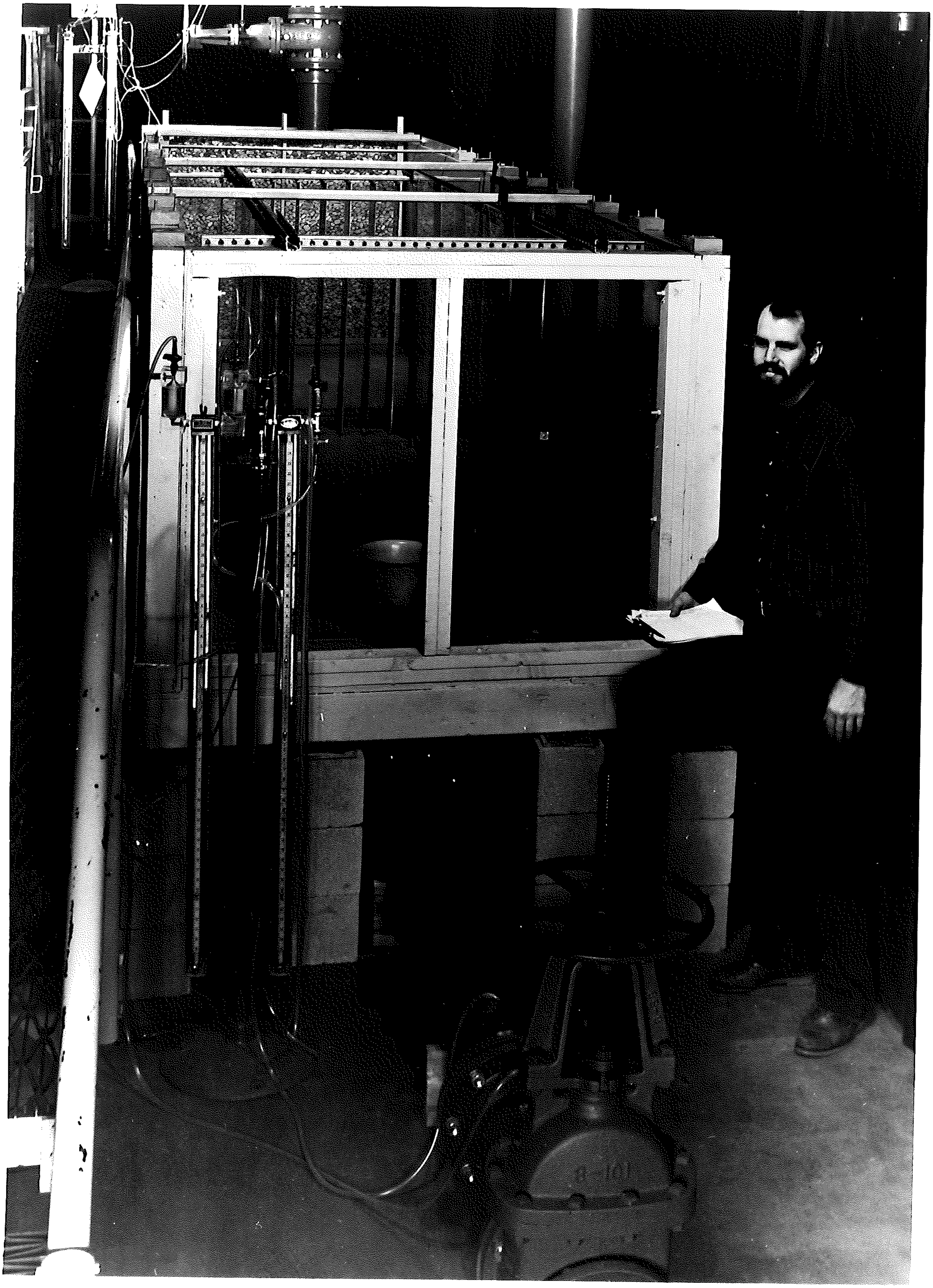


Photo 5. Experimental test facility

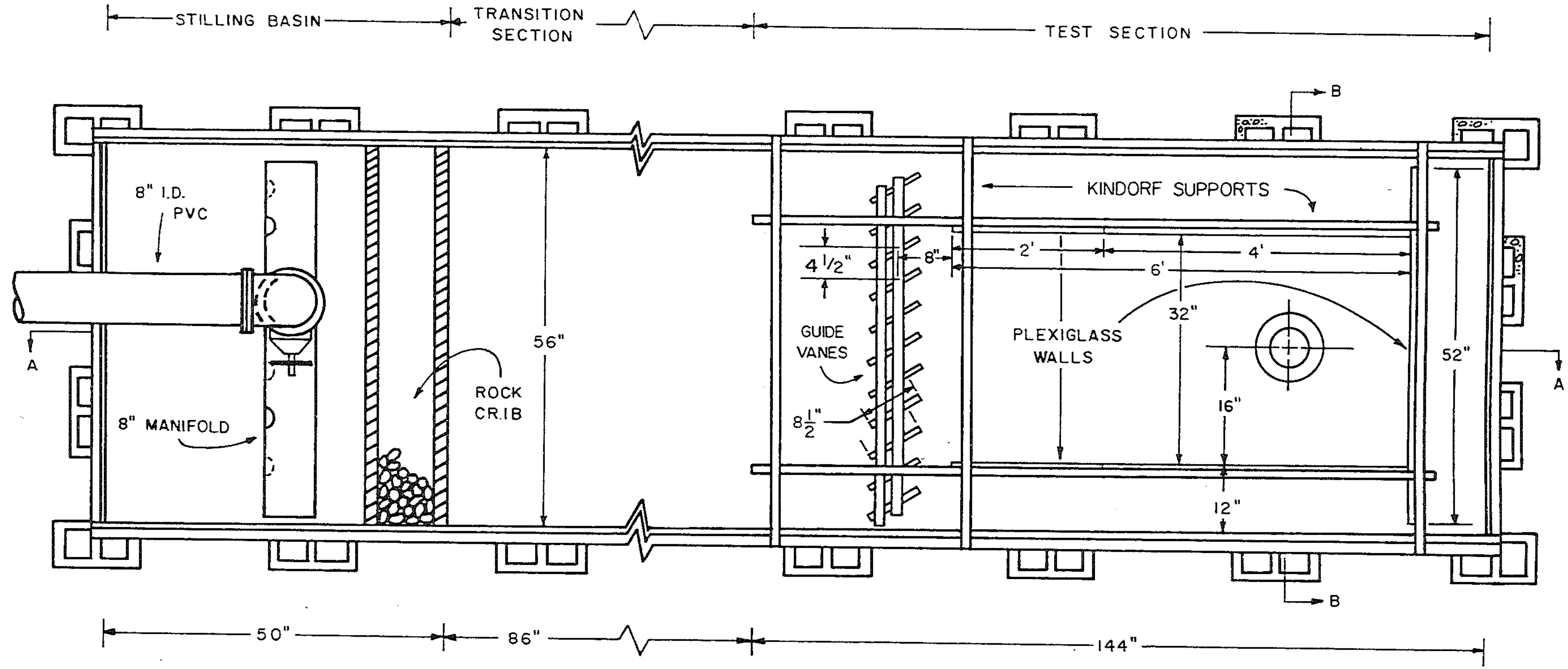
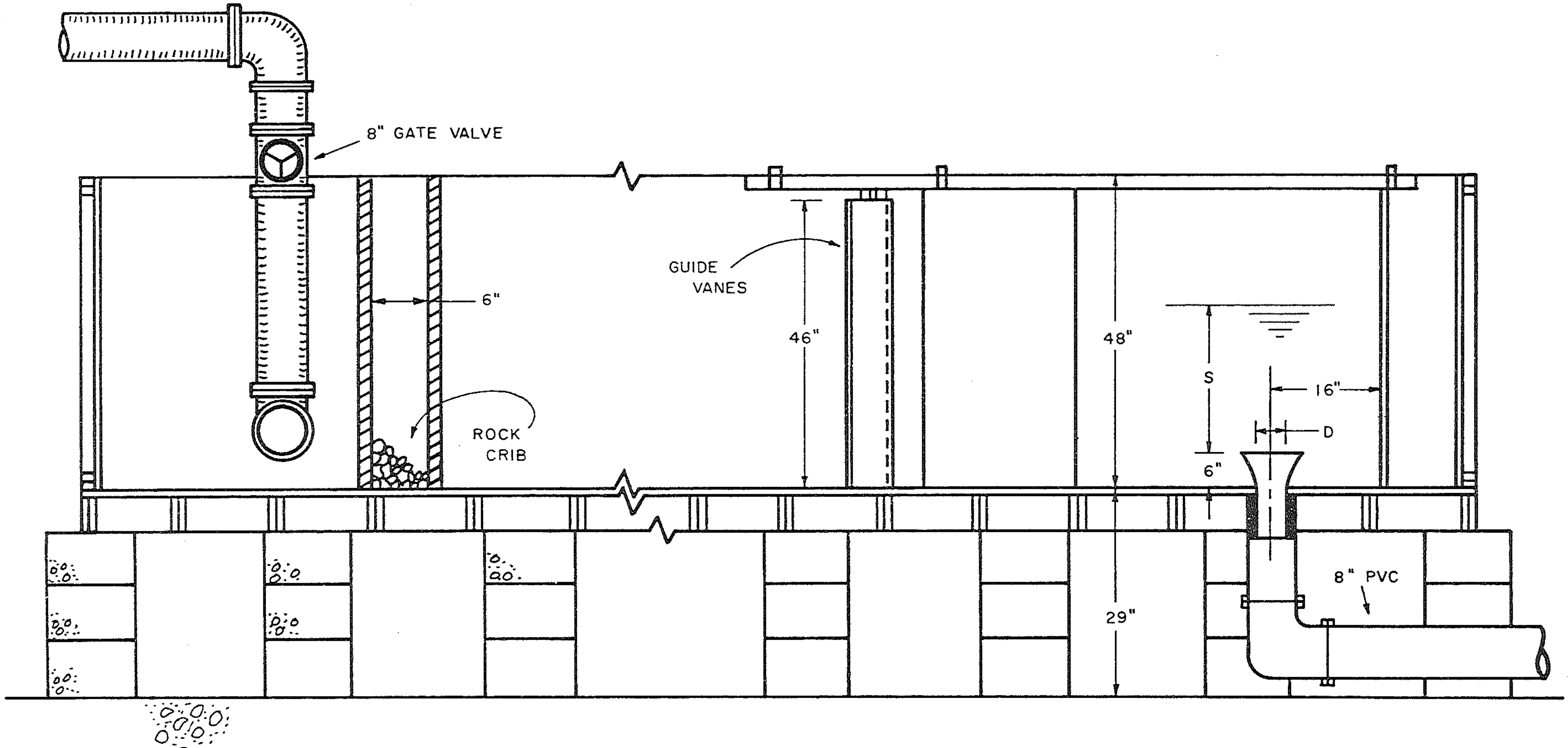


Fig. 20. Plan view of the experimental test facility.



SECTION AA

Fig. 21. Section view of the experimental test facility.

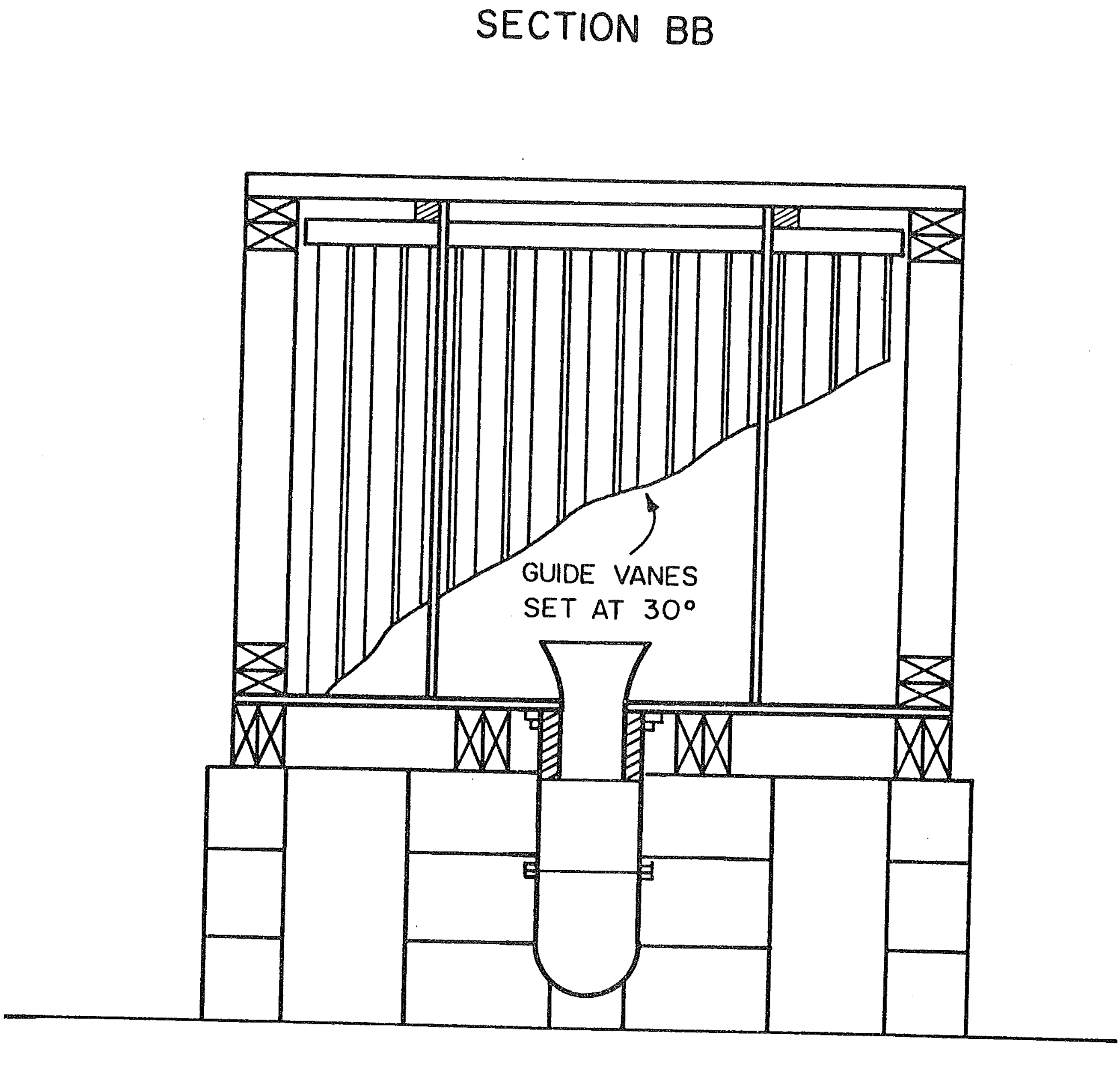


Fig. 22. Section view through the vertical bellmouth intake of the experimental test facility.

During investigation of vortex formation, the headpool elevation above the bellmouth was measured using a conventional point gage. A capacitance wave probe was used to measure the change in headpool elevation with respect to time because of the difficulty in stabilizing the head pool elevation; the instability is described later in this section. The probe was located upstream of the bellmouth such that it would not disturb the vortex formation.

The shape of the bellmouth outlet, as described in the Bureau of Reclamation, Design of Small Dams, is given by the equation

$$\frac{x^2}{(.5D)^2} + \frac{y^2}{(.15D)^2} = 1 \tag{14}$$

where x = horizontal distance, y = vertical distance, D is the diameter of the conduit. In this case D = 6 inches. This equation closely simulates that of a jet discharging into air. This design streamlines the intake such that the bellmouth minimizes head losses and prevents zones where pressures below vapor pressure could develop causing cavitation. This bellmouth shape was chosen to correspond with a common shape found in the field, although the authors believe that the bellmouth shape will not significantly influence free surface vortices.

3. Hydraulic Performance of the Experimental Flume

The hydraulic performance of the flume was found to be acceptable. Prior to the installation of the rock crib, metal screens were used in an attempt to stabilize the flow in the transition zone. This procedure did not appear to work. The flow would find the cracks between the metal screens and small jets would form, causing nonuniformity in the flow. After spending two weeks taking velocity profiles upstream of the test section for various configurations of screens, the screens were discarded and a 6-inch rock crib was used in their place. This proved to be a very acceptable method. The velocity profile given in Table 2 was taken with a hot film anemometer. Twenty velocity measurements were taken at each location, and a numerical average was then calculated to give a temporal mean velocity at each location. The hot film anemometer was calibrated with a Laser Doppler anemometer.

There appears to be some random scatter in the velocity profile given in Table 2. A possible cause for this scatter is that the number of samples taken was not large enough to produce an accurate temporal average. Overall, however, the small velocity difference of ± .02 ft/sec is almost negligible, and therefore the flow can be assumed to be uniform.

In order to evaluate the performance of the guide vanes in predetermining the approach angle, photographs of dye streaklines were taken at two depths and two values of flume discharge. Samples shown in Photos 6 and 7 illustrate the flow separated at the leading edge of one wall, and suppressed boundary layer growth, as anticipated, at the other wall. A small separation zone was formed at the second wall due to resistance to the flow on the outside of the headrace walls (Photo 5). This separation

TABLE 2. Measured Velocities in Vortex Flume Downstream from Rock Crib (ft/s)

Distance from Flume Bottom	WALL			Distance from Walls				WALL Catwalk
	1/2	1	1-1/2	2	2	1-1/2	1	1/2
2.8	.0619	.0462	.0843	.0910	.0810	.0664	.0776	.0664
2.6	.1000	.0641	.0675	.0765	.0720	.0551	.0619	.0641
2.4	.0866	.0933	.0709	.0641	.0574	.0484	.0327	.0596
2.2	.0664	.0978	.0697	.0619	.0450	.0349	.0293	.0630
2.0	.0507	.0866	.0574	.0484	.0383	.0260	.0383	.0619
1.8	.0215	.0753	.0406	.0417	.0428	.0338	.0406	.0529
1.6	.0484	.0596	.0372	.0293	.0462	.0349	.0518	.0450
1.4	.0540	.0462	.0249	.0226	.0372	.0406	.0574	.0327
1.2	.0540	.0484	.0204	.0215	.0249	.0439	.0462	.0551
1.0	.0293	.0338	.0282	.0260	.0103	.0439	.0406	.0417
.8	.0316	.0349	.0428	.0271	.0136	.0394	.0619	.0417
.6	.0293	.0574	.0349	.0237	.0013	.0192	.0596	.0450
.4	.0226	.0394	.0383	.0136	.0394	.0148	.0563	.0574
.2	.0293	.0394	.0372	.0282	.0641	.0933	.1135	.0832
Bottom	.0428	.0372	.0327	.0125	.0866	.1314	.1348	.1112

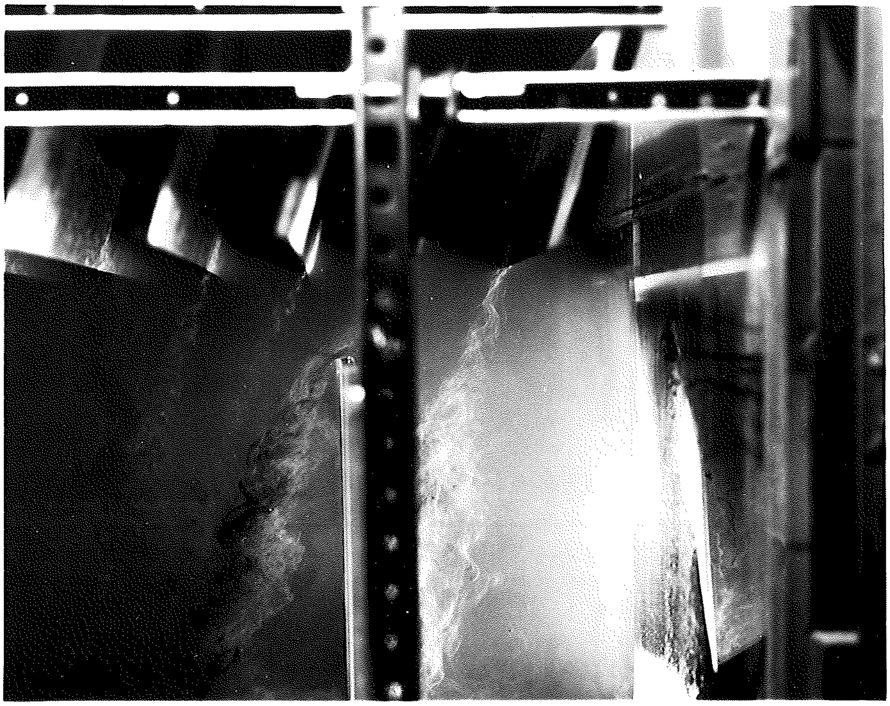


Photo 6. Separation past leading edge of movable wall. Note how well the dye streaklines followed the vanes. S/D = 3.34, F = 2.33, vane angle = 15°.

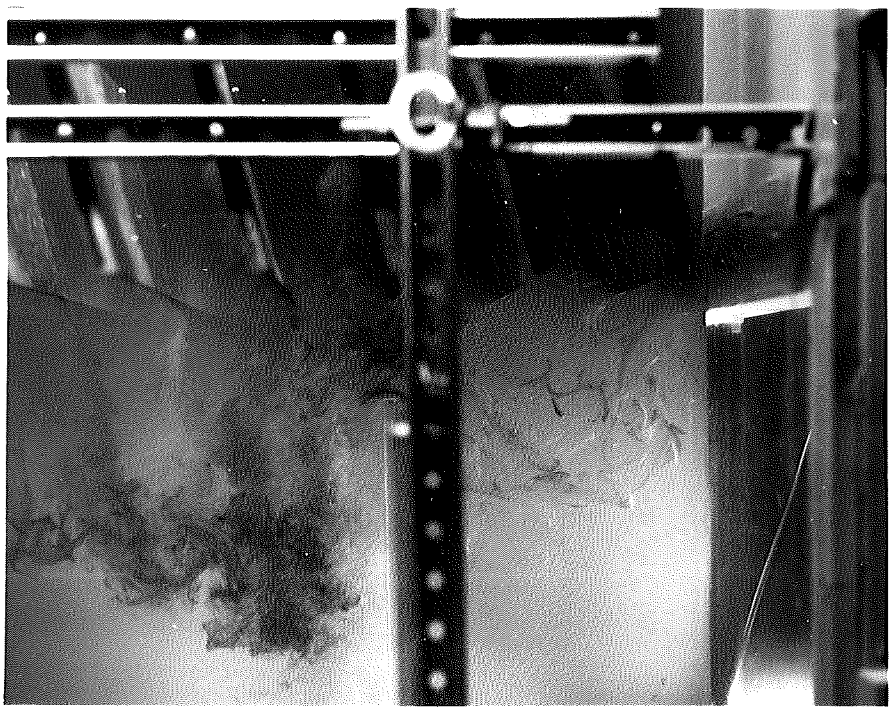


Photo 7. Suppressed boundary layer growth on opposite wall. Note stagnation region in front of wall. S/D = 5.27, F = 2.63, vane angle = 15°.

zone was rapidly suppressed and limited in scope, however, and was not believed to have a significant impact upon approach circulation.

Figures 23 and 24 give sketches of the streaklines at two vane angles. These streaklines indicate that the guide vanes performed their function very well, and that guide vane angle is a good representation of approach flow angle.

B. Experimental Procedure

Preliminary experiments indicated that there existed many different types of vortices at the intake contingent on the flow and submergence of the intake, which confirmed observations in the literature. It was therefore expedient to use some sort of classification scheme to describe the vortices observed. Durgin and Anderson [25] used the scheme shown in Fig. 25. This scheme rates the strength of a vortex by a visual observation of the surface activity above the intake, and represents the full range of possible surface activity.

For a vertical intake, however, it was found that some of these types of activity were difficult to identify separately. In most intake configurations there are other phenomena present besides intake withdrawal which can cause Type 1 (surface swirl) and Type 2 (surface dimple) activity. In the experimental vortex flume, for example, separation of the approach flow around the leading edge of headrace walls produced both of these types of activities independent of the intake operation. Type 0 (no activity) was therefore rare, and Types 1 and 2 were relatively common, with no relation to free surface vortex formation. These types of surface activity were, therefore, not incorporated into the visual observations.

It was also difficult to distinguish between Type 4 activity (vortex pulling trash) and Type 5 activity (vortex pulling air bubbles). The transition between Type 4 and Type 5 activity was momentary at best, and was therefore not considered descriptive. Thus, Type 5 activity, which required no addition of confetti to simulate trash, was used to identify vortex strength.

This leaves three types of surface activity which are believed to be descriptive of vortex strength in the experimental flume:

Type 3: A continuous dye core reaching into the intake, as shown in Photo 8.

Type 5: A vortex entraining bubbles into the intake, but with no coherent air core, shown in Photo 9.

Type 6: A vortex pulling air continuously into intake, shown in Photo 10, which was identified by an audible noise.

Even though only three types of surface activity are identified as representative, the classification given in Fig. 25 is retained to avoid confusion in the literature. It is also possible that the above observations

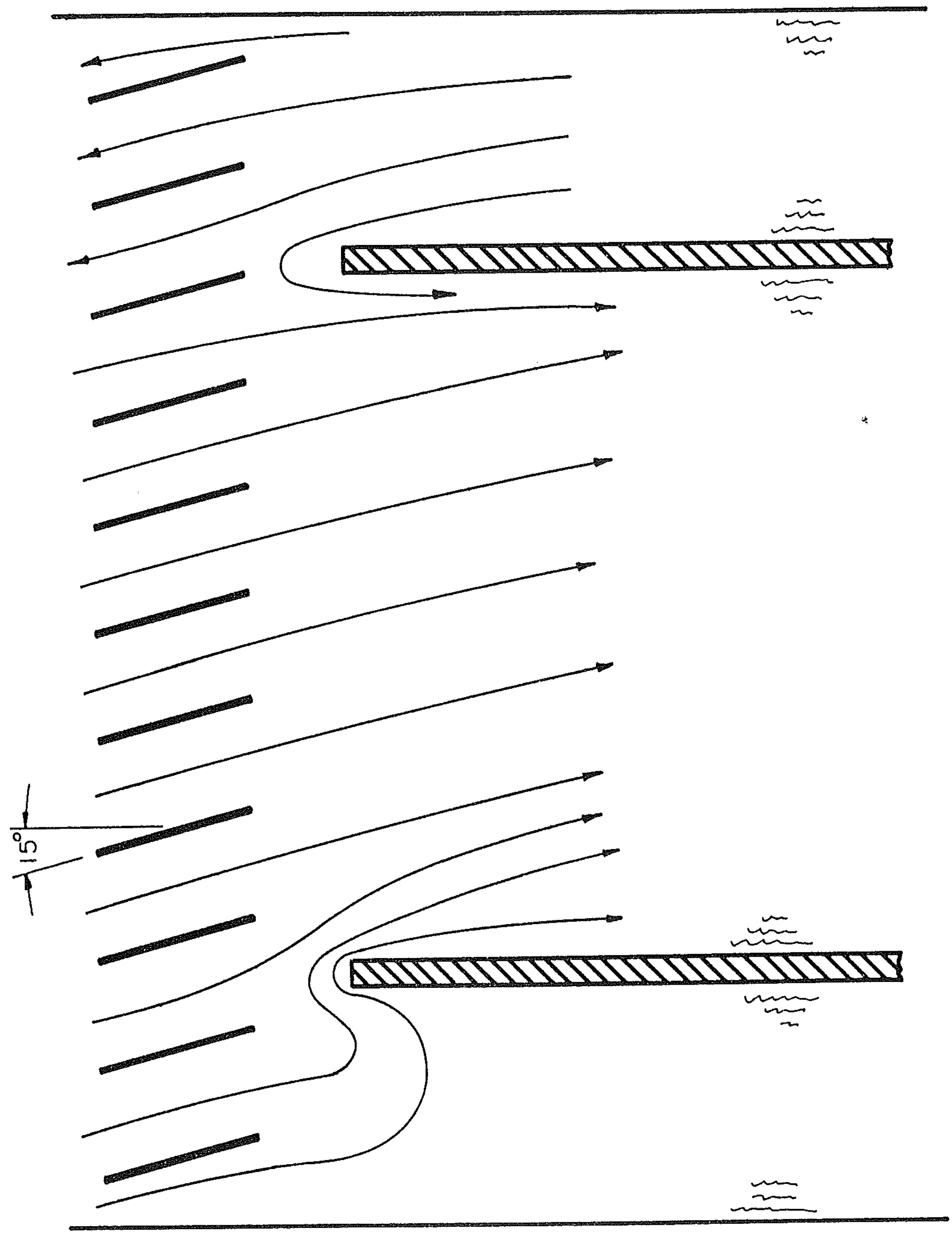


Fig. 23. Dye streaklines for S/D = 5.02, F = 3.59; vane angle set at 15°.

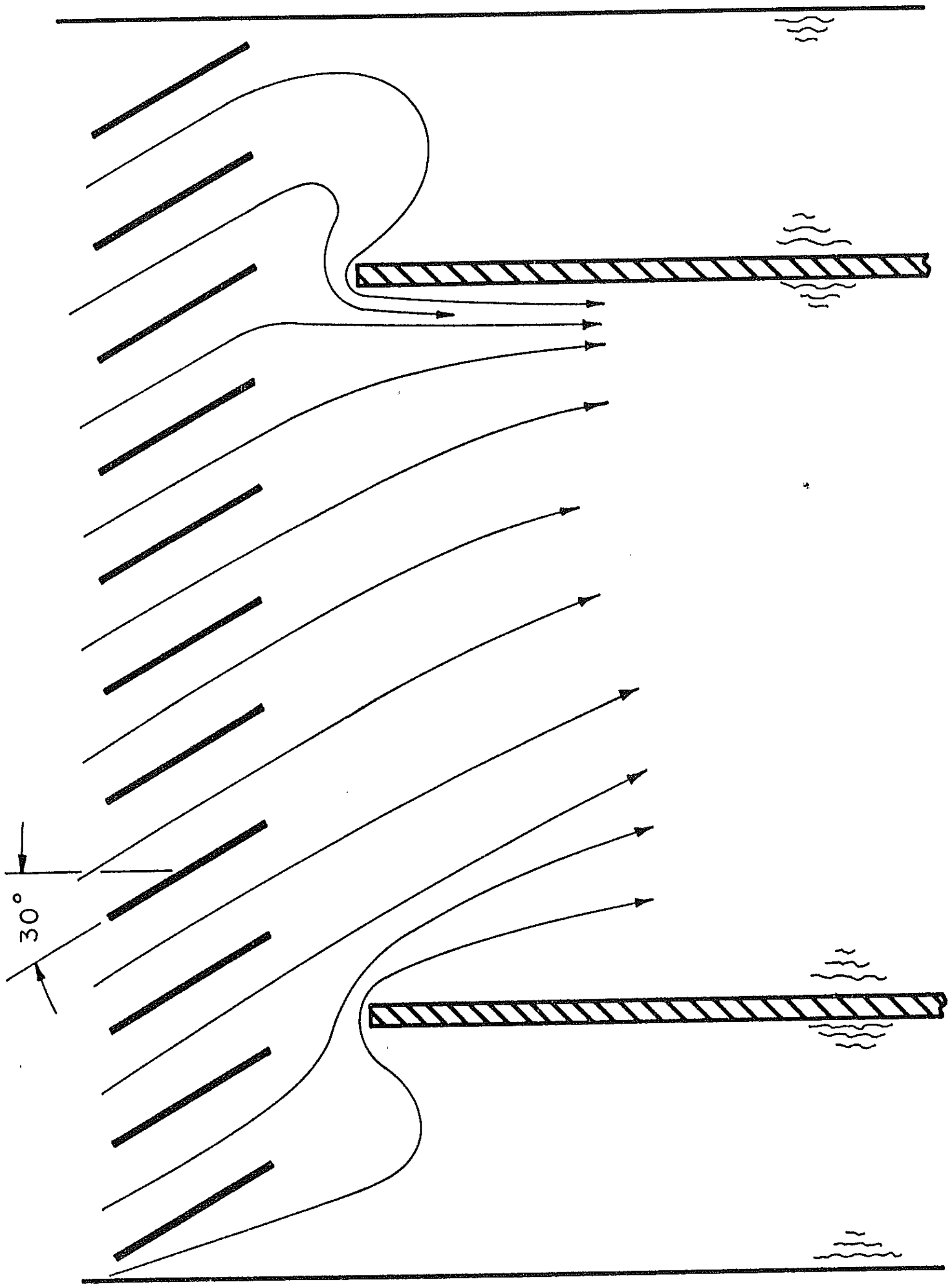


Fig. 24. Dye streaklines for S/D = 4.39, F = 3.59; vane angle set at 30°.

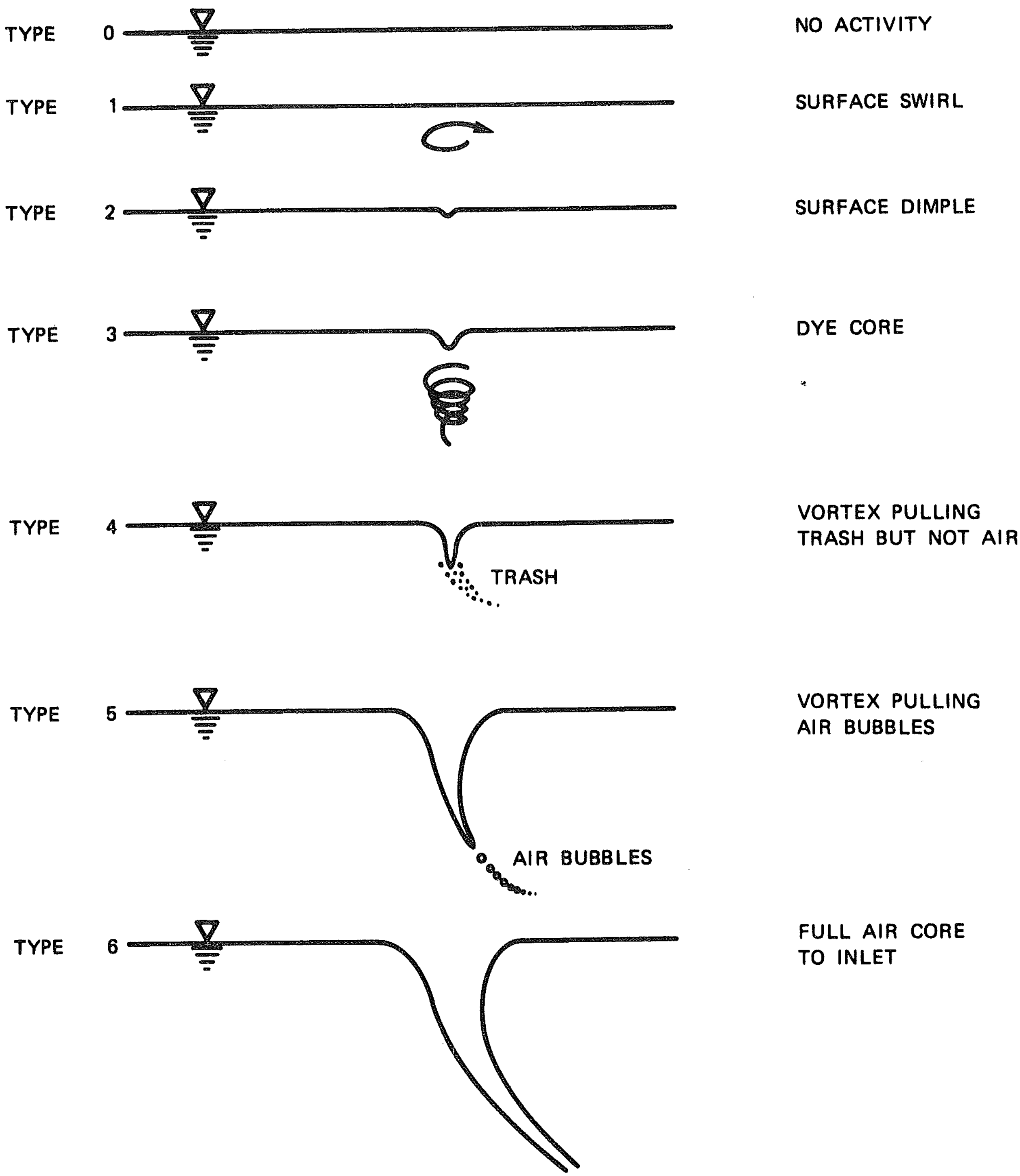


Fig. 25. Vortex strength scale used by Durgin and Anderson [25] for classification of free surface vortices at intakes.

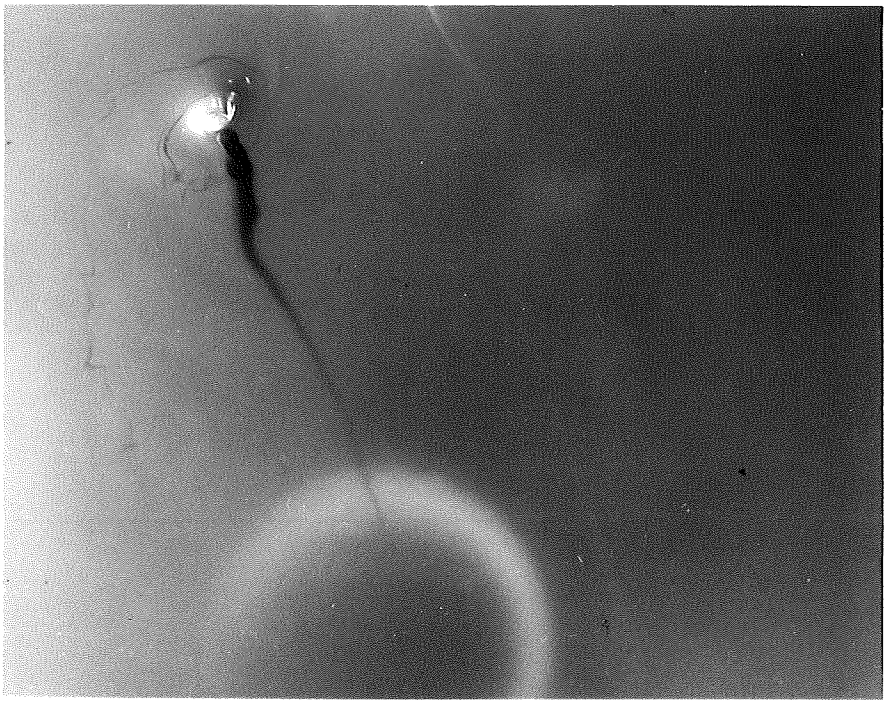


Photo 8. Dye core vortex, Type 3.

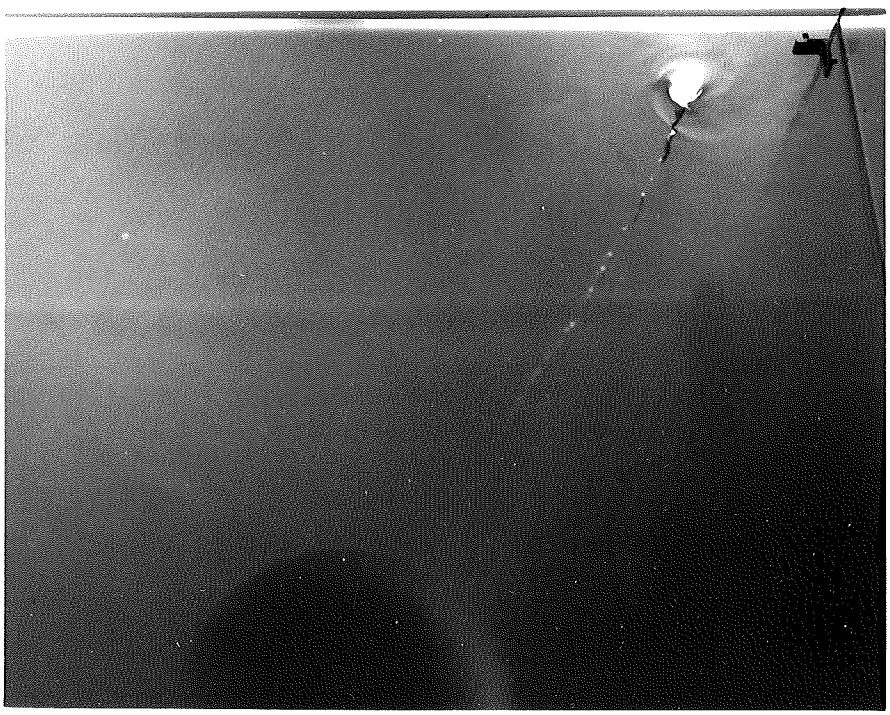


Photo 9. Bubble entraining vortex, Type 5.

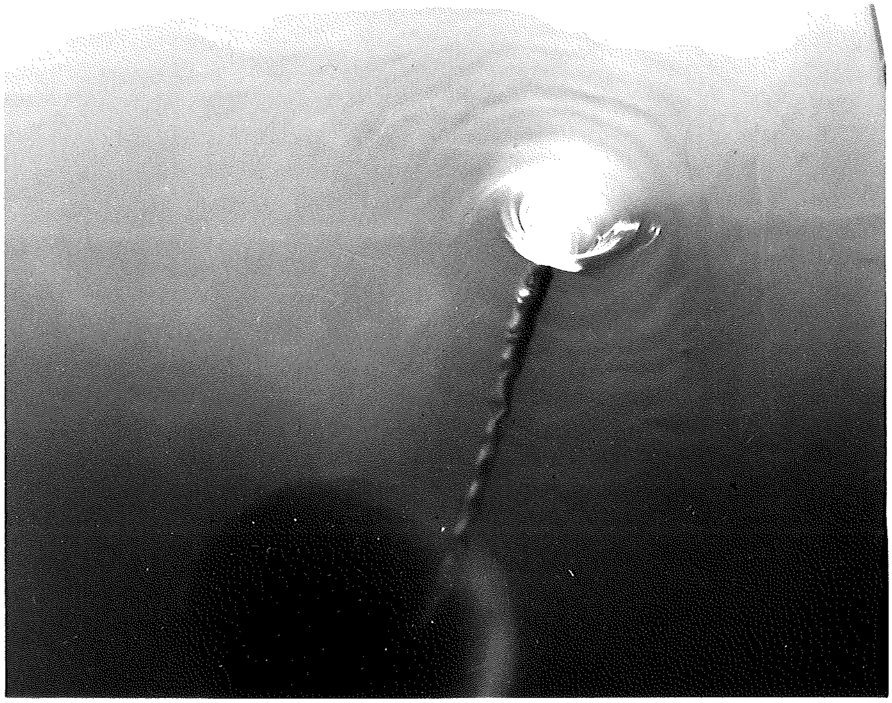


Photo 10. Air entraining vortex.

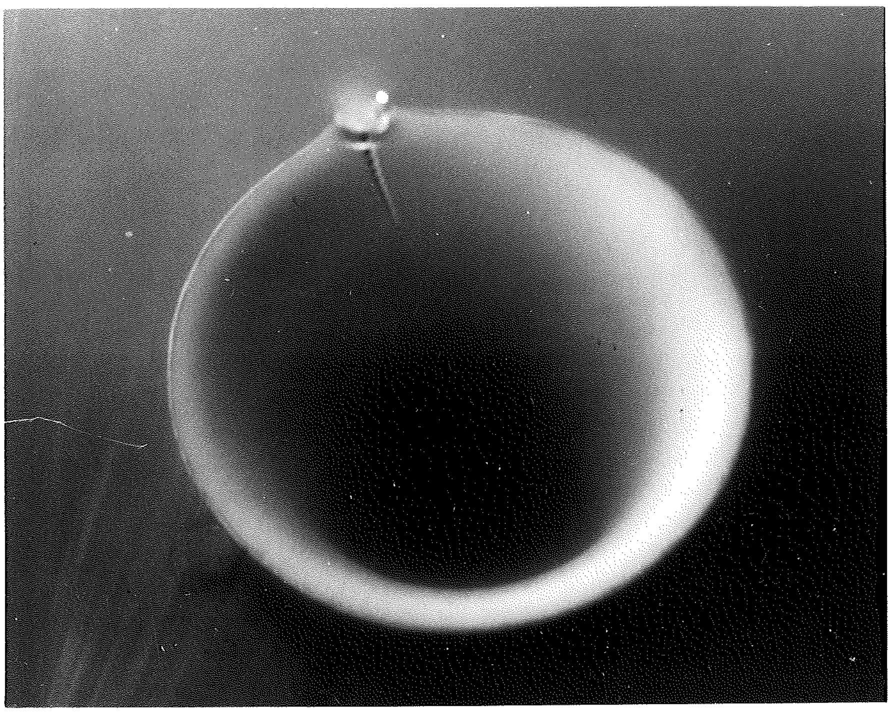


Photo 11. Viscous dimple which occurred in place of a bubble entraining vortex, or an air entraining vortex, at Fr $\leq$ 0.85.

are not valid for inverted intakes, where surface swirls and dimples caused by intake withdrawal may be more easily identified. The surface activity Types 3, 5, and 6 were thus used to identify vortex strength in the experiments. There was, however, one type of surface activity which this classification failed to identify. This surface activity, labelled a viscous dimple, is shown in Photo 11. The viscous dimple is a relatively deep dimple which occurs in place of Type 5 or Type 6 activity at low intake velocities. At intake Froude numbers, $F < 0.85$ the viscous dimple occurred in place of the air-entraining vortex, Type 6. When $F \leq 0.45$, the viscous dimple occurred in place of either Type 5 or Type 6 activity. This may indicate significant viscous effects upon vortex formation at intake Froude numbers less than 0.85 in the flume, corresponding to an intake Reynolds number $Re = VD/\nu \leq 10^5$. The implication here is that neither Jain et al.'s [4] criteria, $Re \geq 5x10^4\ \nu/\sqrt{gD}$ or Dagget and Keulegan's criteria [6], $Re \geq 3.2x10^4$ for avoiding viscous effects in intake vortices is conservative. The remainder of this section describes the method by which the intake submergence and discharge were determined when each type of activity occurred.

One method of determining the type of surface activity occurring from a given submergence and discharge is to stabilize the water surface elevation. If the water surface elevation is stable, the inflow into the flume must equal the outflow of the flume. For weir flow the pool elevation stabilizes very quickly, but for full pipe flow, as the inflow and outflow of this flume, a stable pool elevation requires a long stablization period. This is complicated by the fact that inflow and outflow discharge must be matched, which involves two independent valves. Matching these valves is virtually impossible. Consequently, another method was chosen to measure the submergence and discharge corresponding to a particular surface activity.

This method is similar to the method used by Blaisdell and Donnelly [26] and Humphey et al. [17] coined by Blaisdell et al. as "taking data on the run." Blaisdell et al.'s method requires the water surface elevation to be continually monitored, and allows the water surface elevation to fluctuate. For a constant inflow, the outflow can then be calculated easily by adding or subtracting the amount of flow rate coming out of or going into the storage of the flume, respectively. The amount of inflow going into or coming out of storage can easily be calculated by using time rate of change of water surface elevation, multiplied by the surface area of the flume to give units of discharge. One precaution is that the water surface elevation cannot change too rapidly because a given time is required for the large vortex flow structure to develop.

Since the inflow rate to the flume was continuously changing, owing to the drop in water surface elevation in the flume, as well as the Mississippi River pool elevation, the inlet discharge was monitored continuously instead of being assumed constant, and noted on the strip chart. In addition, the strip chart record of water surface elevation was calibrated frequently. Two people were required to take data for an experimental run, one person to read off point gage values and identify surface activity, and another person to monitor the inflow discharge and make notations on the chart recording. The information noted on the chart recorder was the upstream manometer deflection, the surface activity, and point gage reading over time.

A typical run for a given intake Froude number would begin with closure of the downstream valve such that the water surface elevation would rise in the flume. Once the water surface elevation was raised to a sufficiently large depth, the inflow manometer would be set to a manometer deflection corresponding to the intake Froude number desired. The downstream valve would be opened and as the water surface elevation fell, surface point gate readings would be taken. The surface activity corresponding to a certain vortex intensity, when it first occurred, would be noted on the chart recording. The run would continue until a Type 6 vortex entraining air would first occur.

This procedure was found to be relatively fast and reproducible. In addition, it reduced the many variables to be controlled simultaneously in the flume. An analysis of the impact of variable water surface elevation on the results is included in Section IV.C.

C. Results

1. Presentation of Results

The purpose of the experimental study was to initiate development of design information to assist an intake designer in the avoidance of free-surface vortices. The results are given in Fig. 26 through 36 for various combinations of approach vane angle and channel length. Each figure may be segmented into three zones of critical submergence. The first zone is the submergence versus intake Froude number range in which dye core vortices will form (Type 3). The second zone is the submergence versus intake Froude number range in which bubble entraining vortices form (Type 5), and the third zone is that zone where air entraining vortices form (Type 6).

A good example of these zones are shown in Fig. 33 for 30° vane angles and 6 ft canal wall length. The lines drawn are envelope curves defined as that curve which encompasses most, if not all, observations, of a particular type of vortex. It should be pointed out that there are two types of data shown in this figure. The first type of data given by unshaded symbols were taken using the procedure outlined in the previous section. The shaded data points were taken using a procedure which stablized the water surface elevation in the flume. The water surface elevation of the supply pool became stable during the summer and this led to the ability to stablize the water surface elevation in the flume, with very small changes in the downstream value. The data indicate that the assumption that a slow change of water surface elevation does not affect the formation of vortices lead to a persistent error in critical submergence. This is easily seen from the envelope curves for bubble entraining and air entraining vortices in Fig. 37. The submergence requirement envelope curves for the bubble entraining vortices and the air entraining vortices are higher for the steady stage data. When compared to the scatter in the measurements, however, this error is not exceedingly large.

The dye core vortices did not show this difference between the two types of data. This result is significant since it means the envelope curves developed from the less tedious "on the run" measurements are a true indication of the minimum submergence required to avoid dye core vortices.

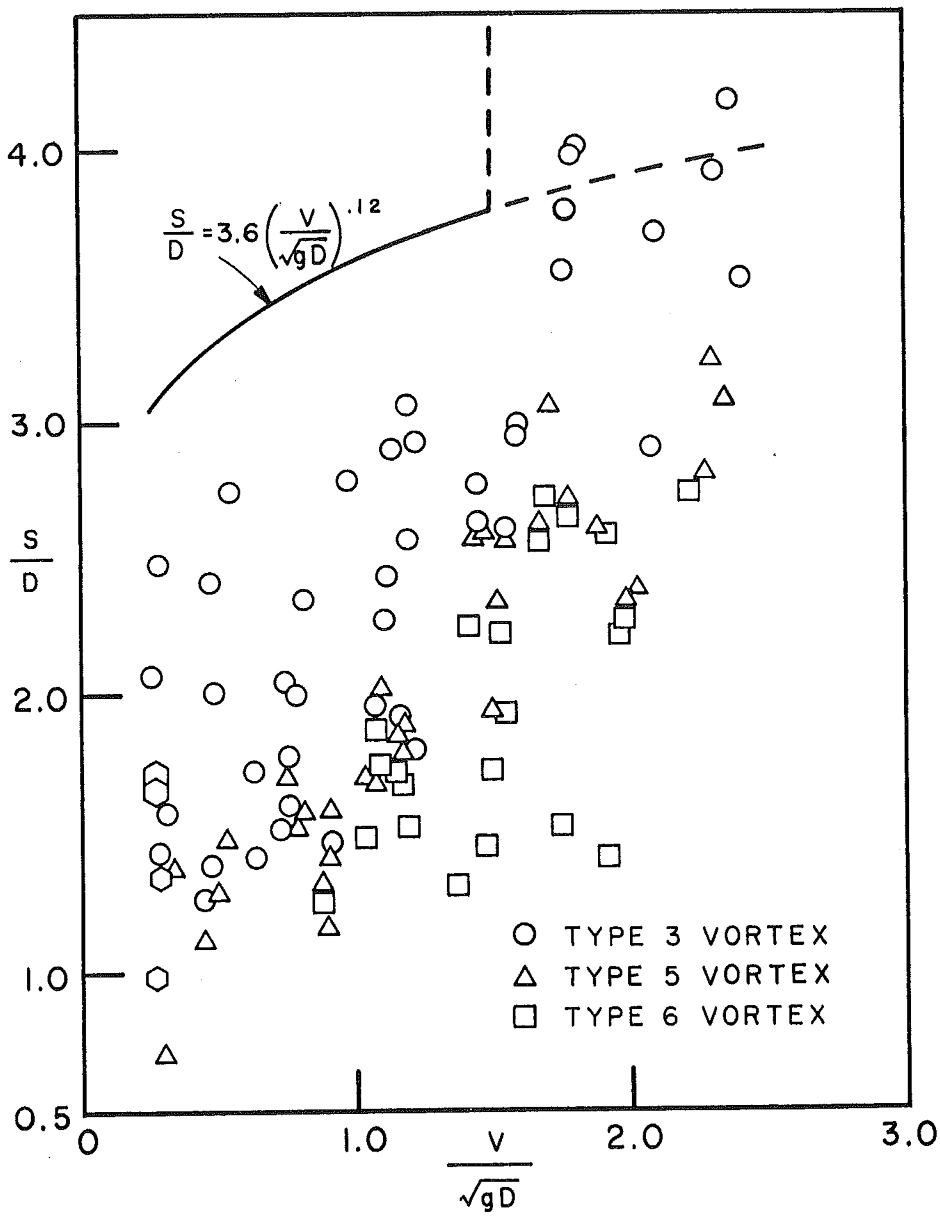


Fig. 26. Dimensionless submergence versus intake Froude number for 0° vane angle and L/W = channel length/width ratio = 1.13. Hexagon symbol indicates viscous dimple.

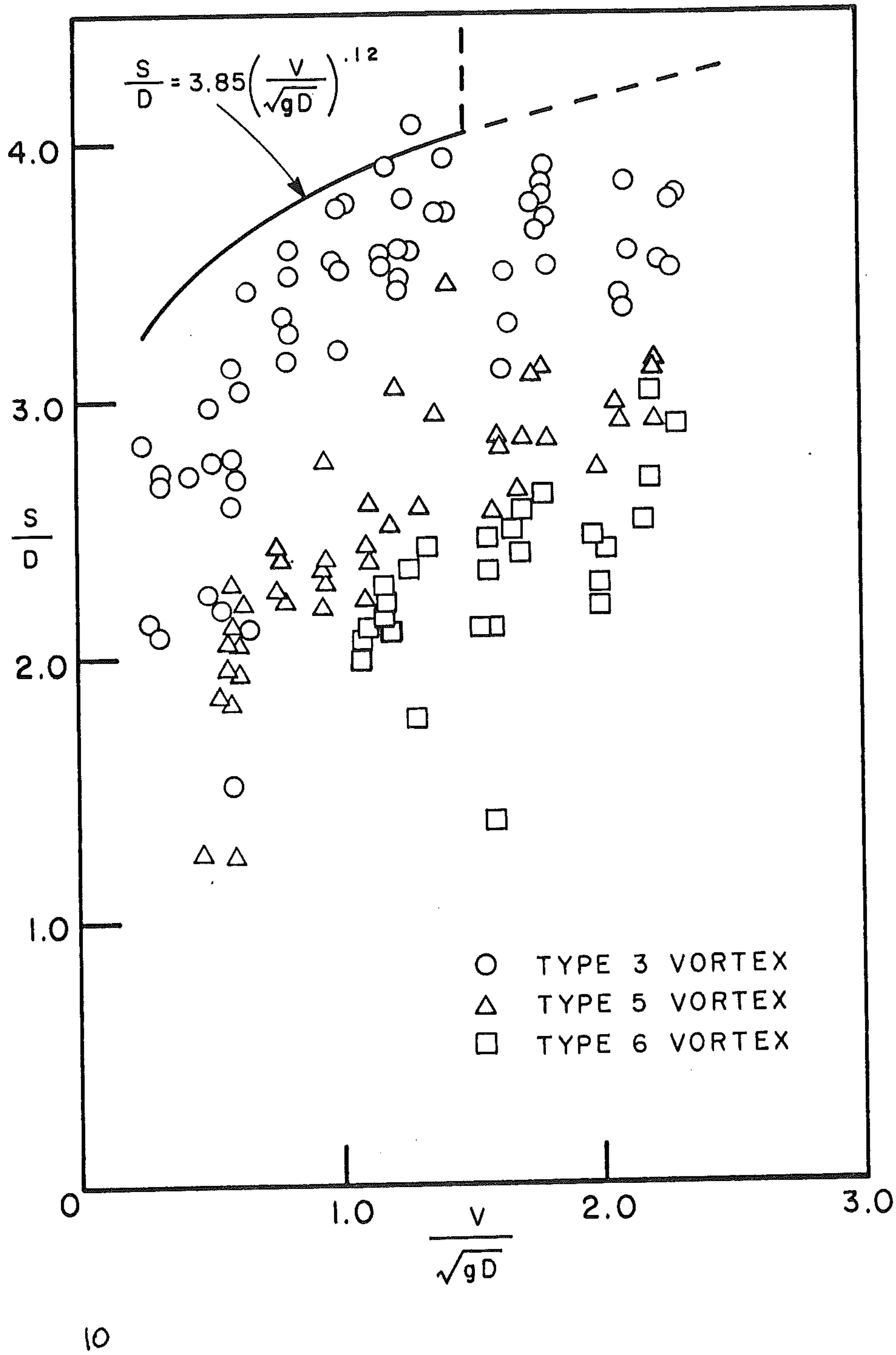


Fig. 27. Dimensionless submergence versus intake Froude number for 7.5° vane angle and L/W = 1.13.

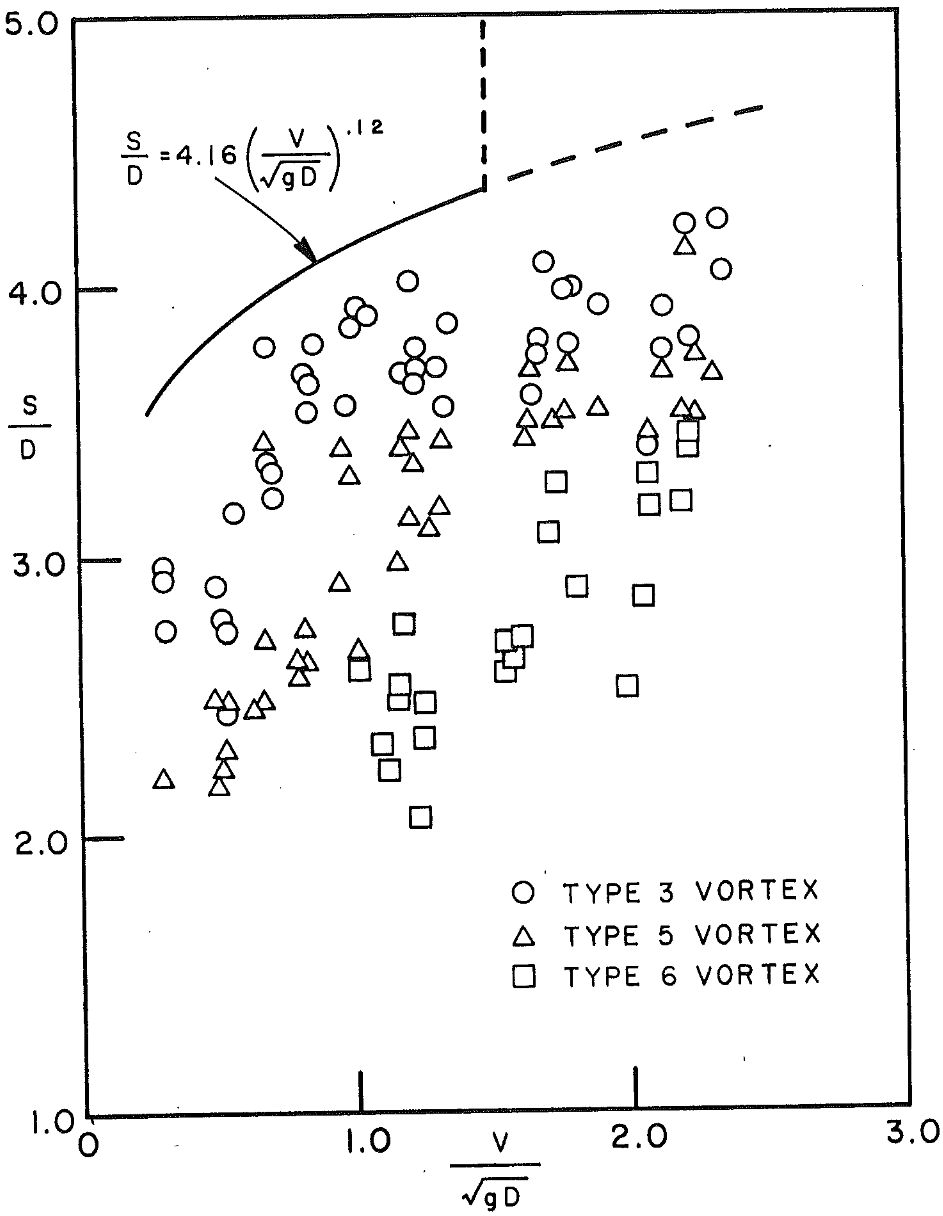


Fig. 28. Dimensionless submergence versus intake Froude number for 15° vane angle and L/W = 1.13.

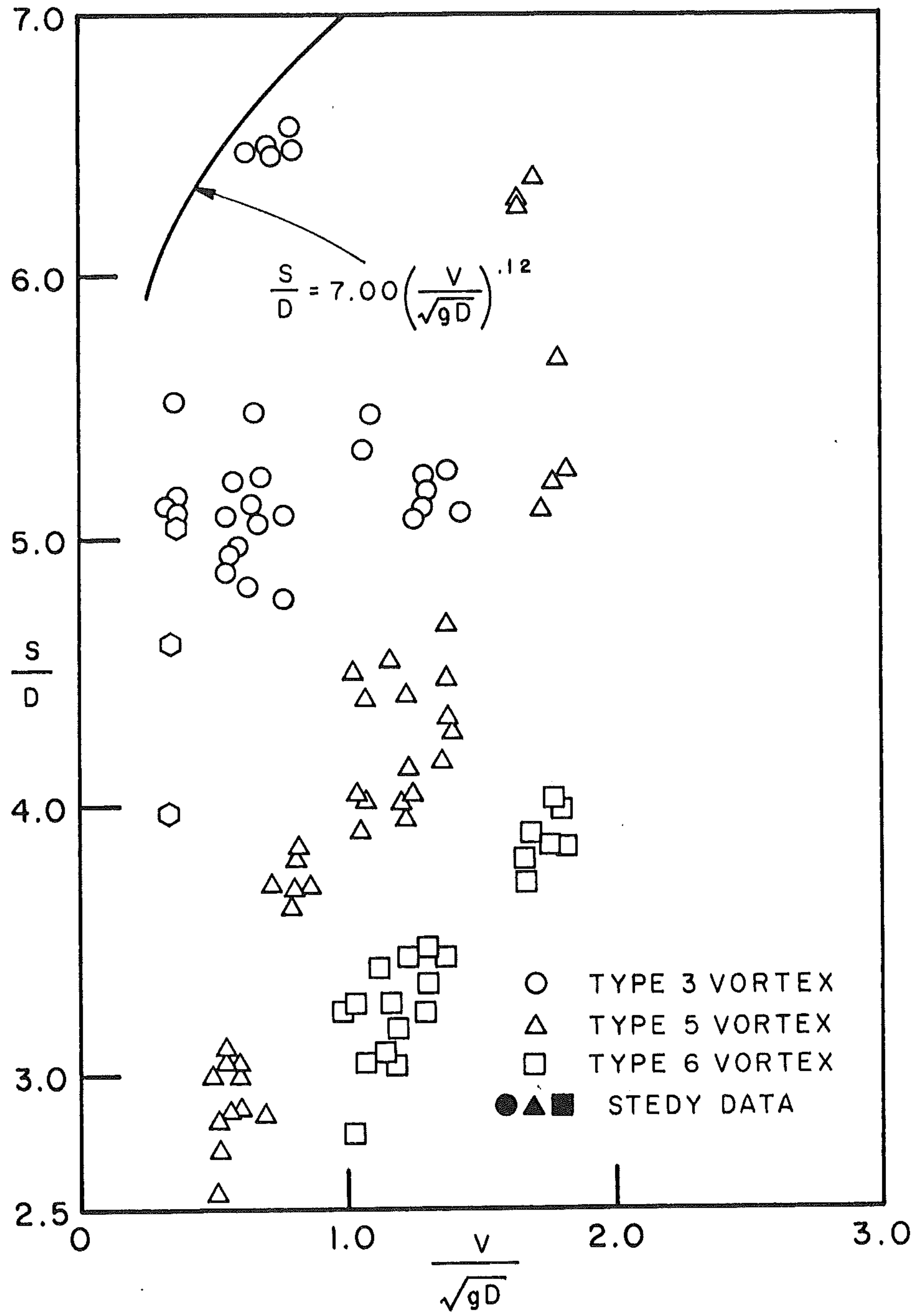


Fig. 29. Dimensionless submergence versus intake Froude number for 30° vane angle and L/W = 1.13. Hexagon symbol indicates viscous dimple.

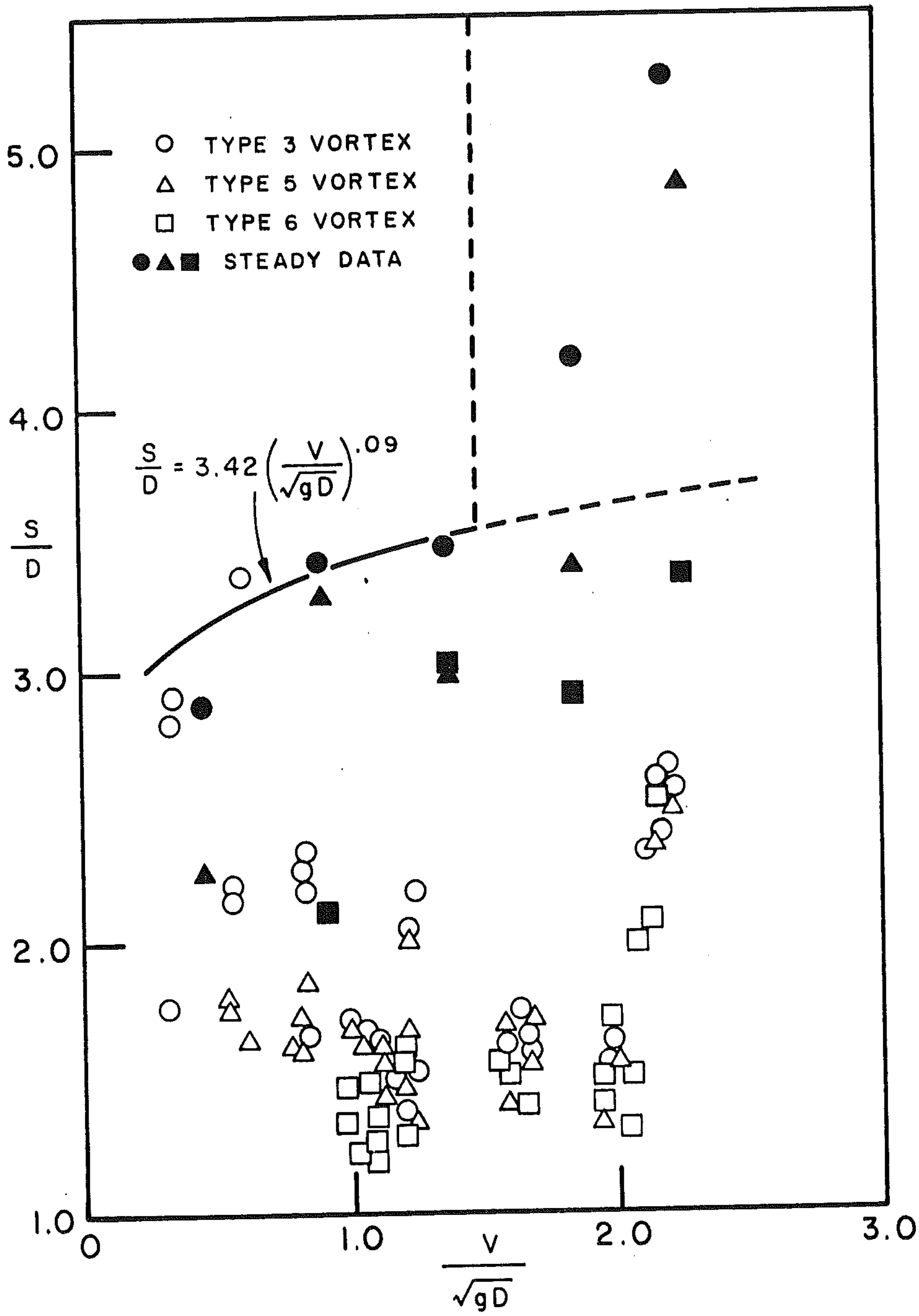


Fig. 30. Dimensionless submergence versus intake Froude number for 0° vane angle and L/W = 2.25. (Note: data taken with a stable stage is shaded.)

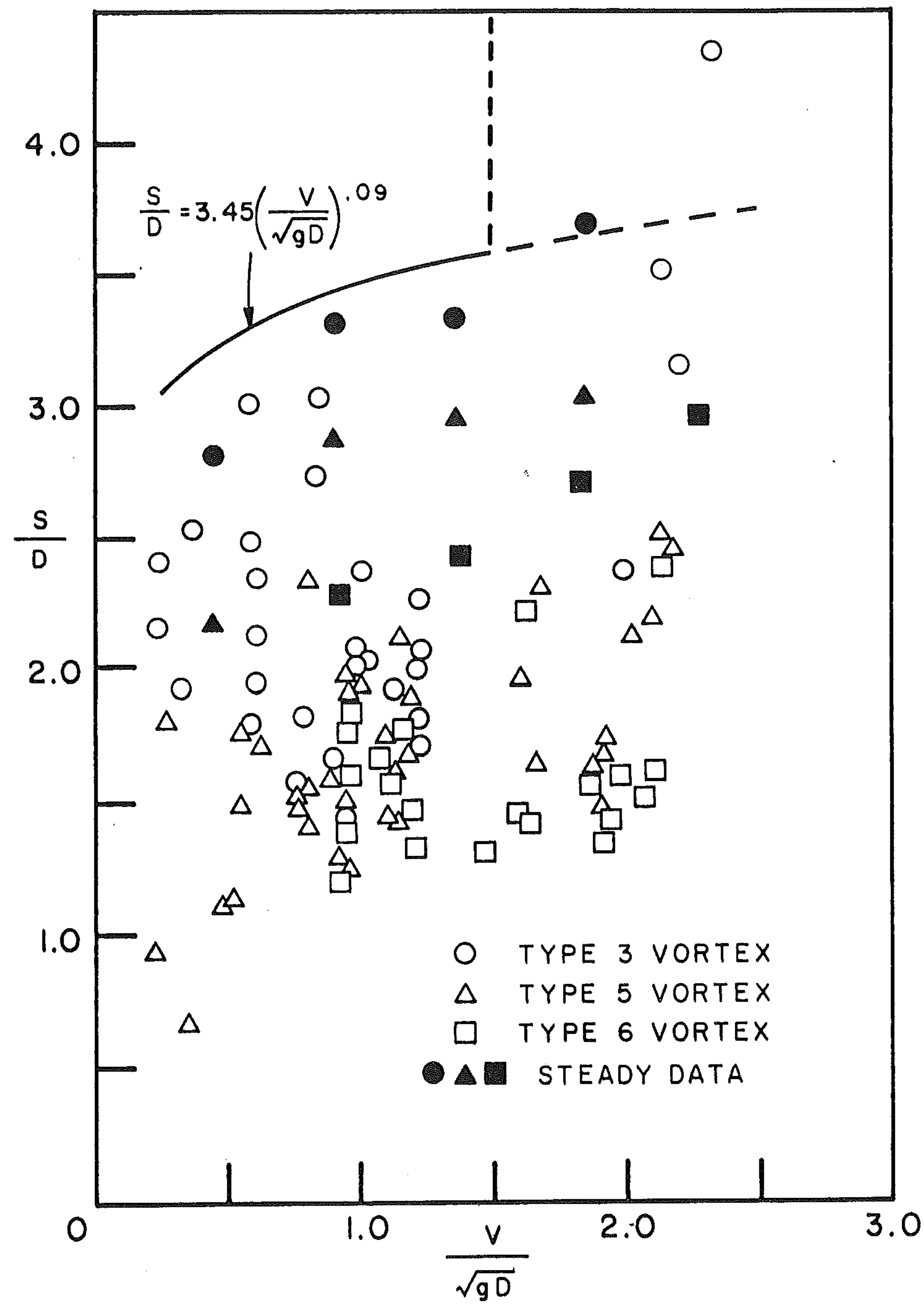


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Fig. 31. Dimensionless submergence versus intake Froude number for 7.5° vane angle and L/W = 2.25. (Note: Data taken with a stable stage is shaded.)

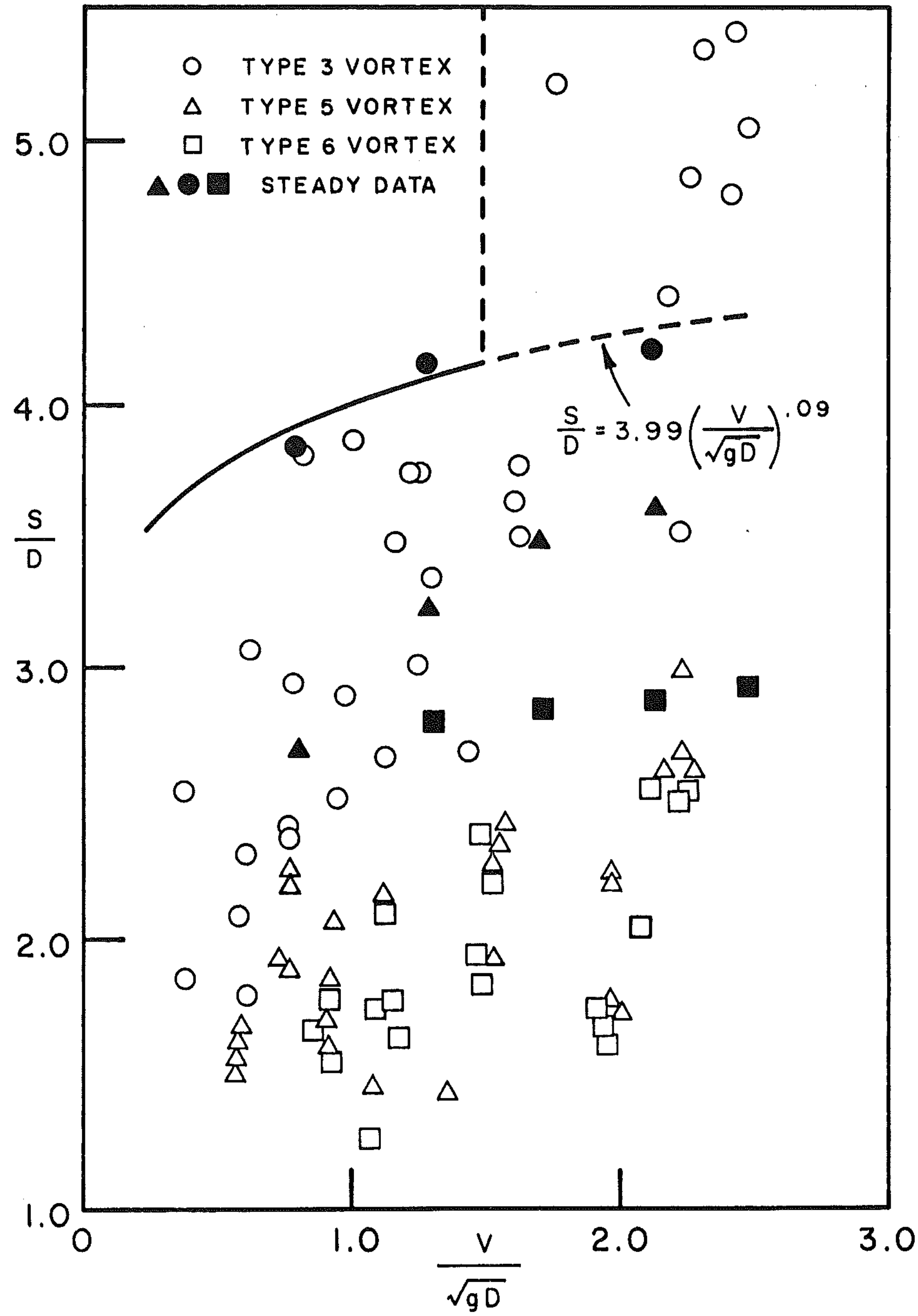

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Fig. 32. Dimensionless submergence versus intake Froude number for 15° vane angle and L/W = 2.25. (Note: data taken with a stable stage is shaded.)

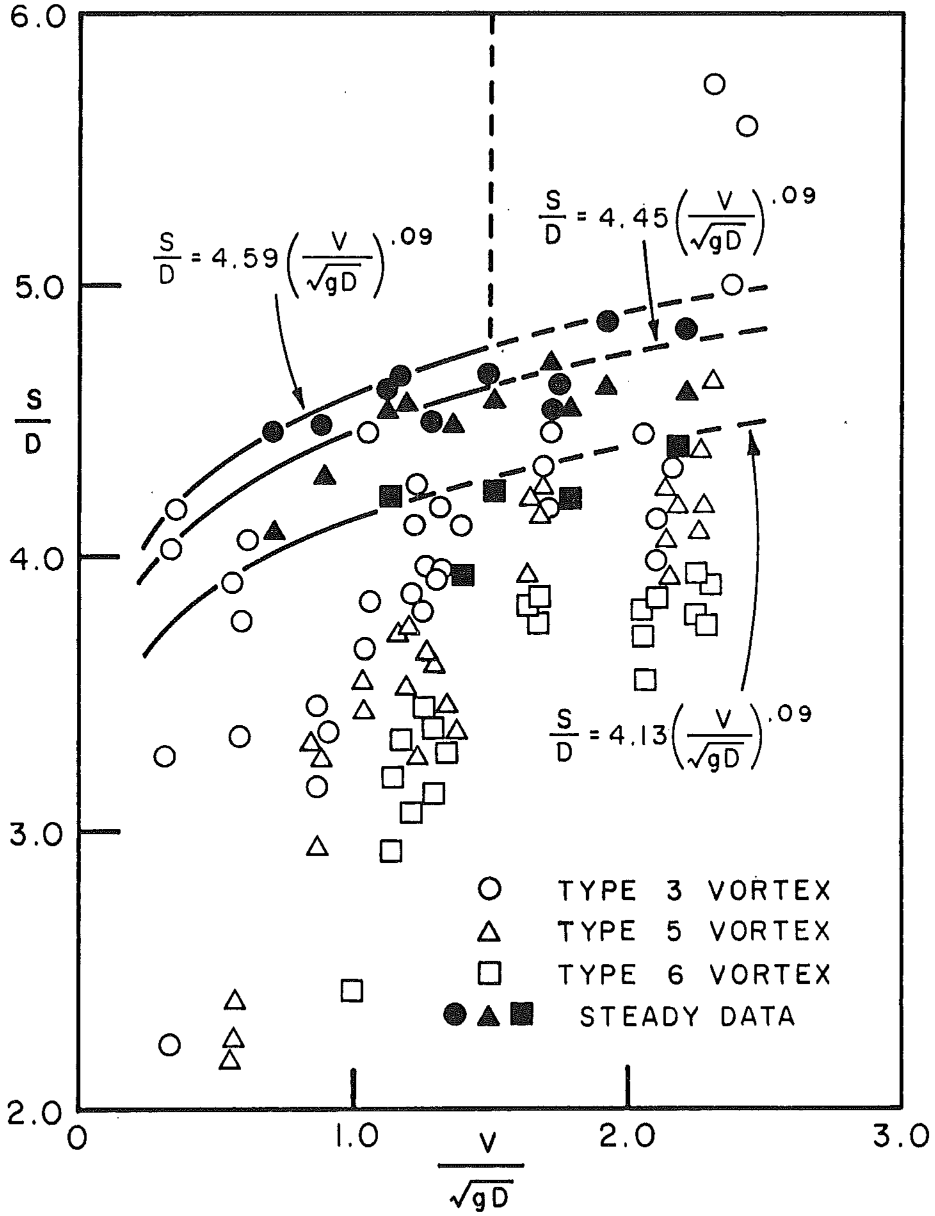

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Fig. 33. Dimensionless submergence versus intake Froude number for 30° vane angle and L/W = 3.56. (Note: data taken with a stable stage is shaded.

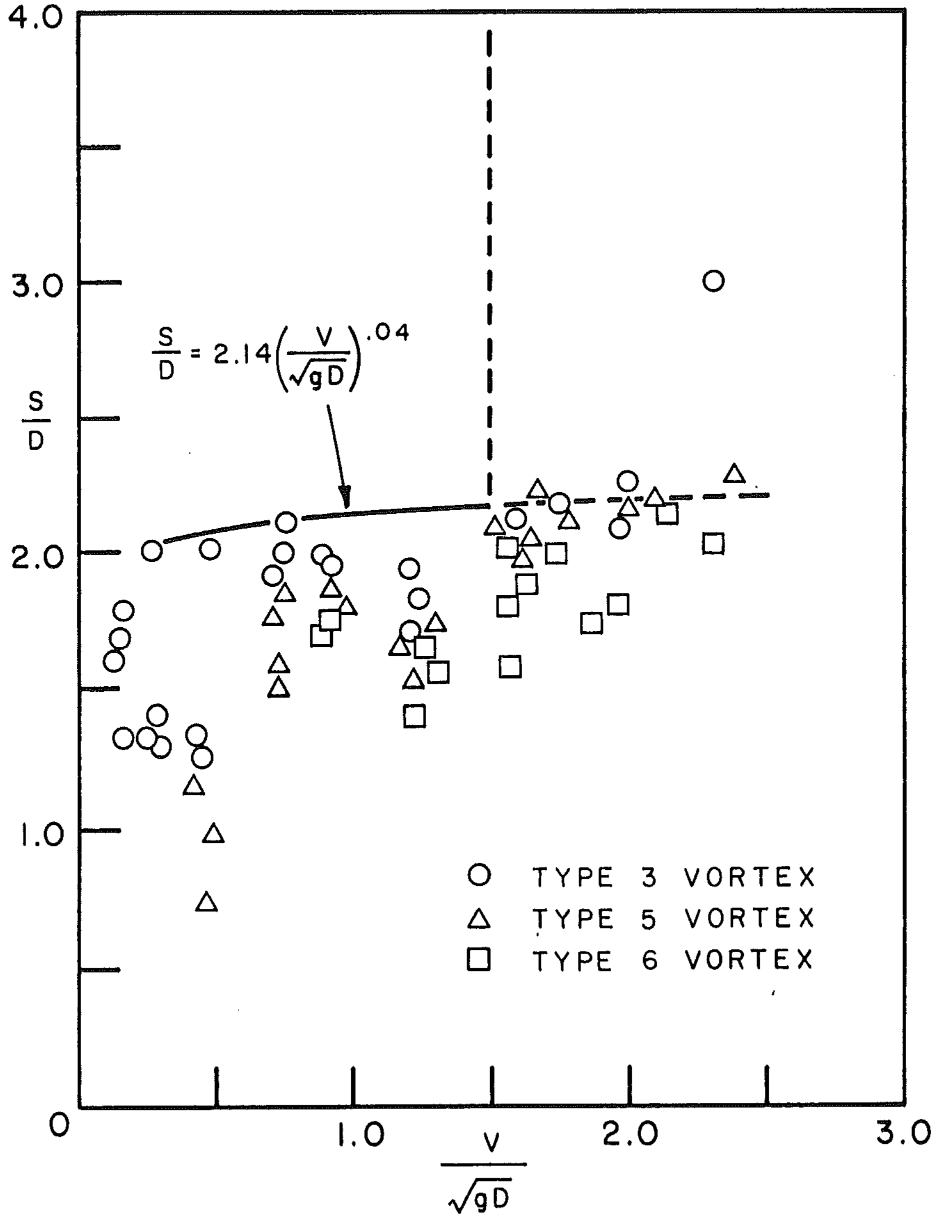

Fig. 34. Dimensionless submergence versus intake Froude number for 0° vane angle and L/W = 3.56.

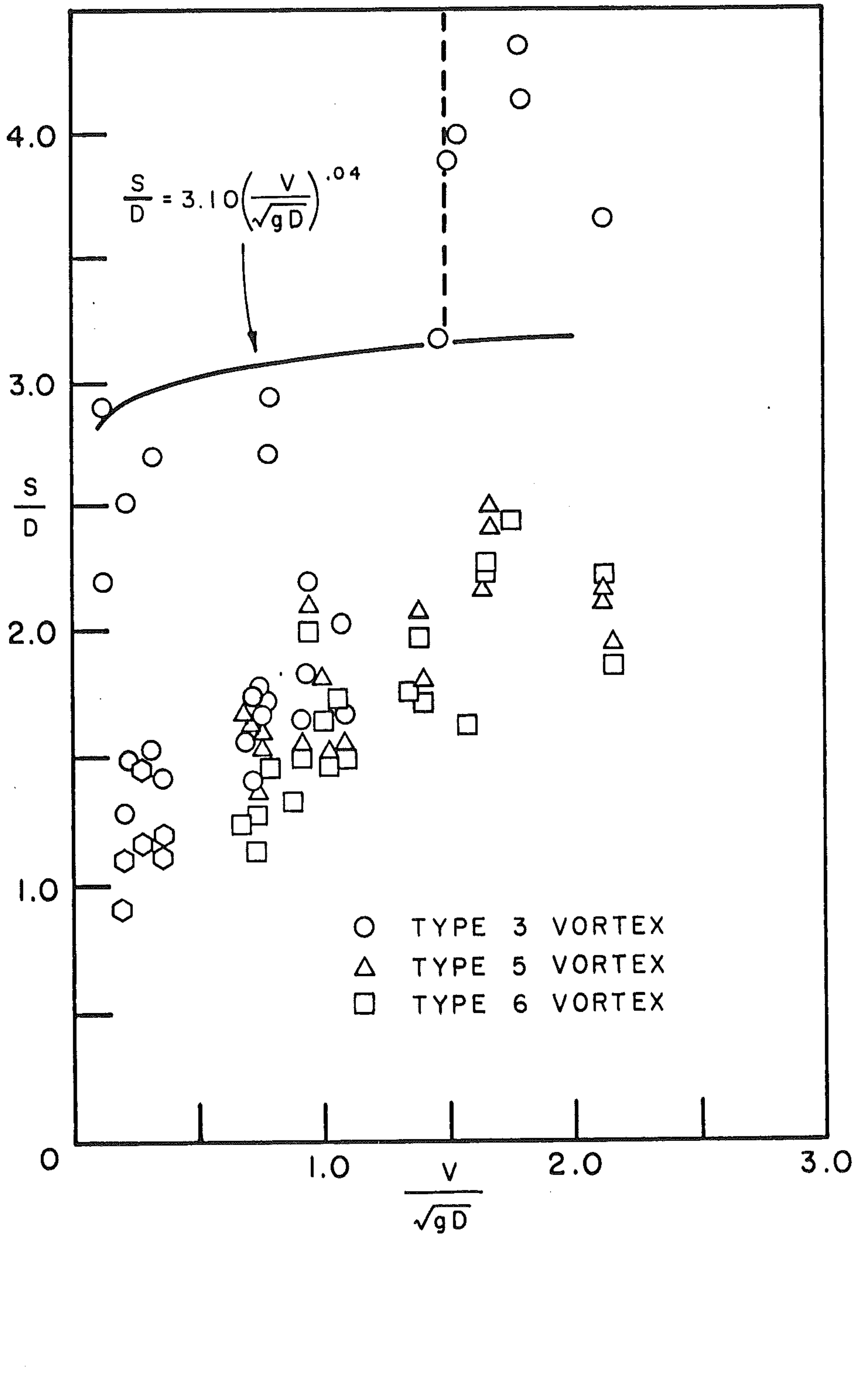

Fig. 35. Dimensionless submergence versus intake Froude number for 15° vane angle and L/W = 3.56. Hexagon symbol indicates viscous dimple.

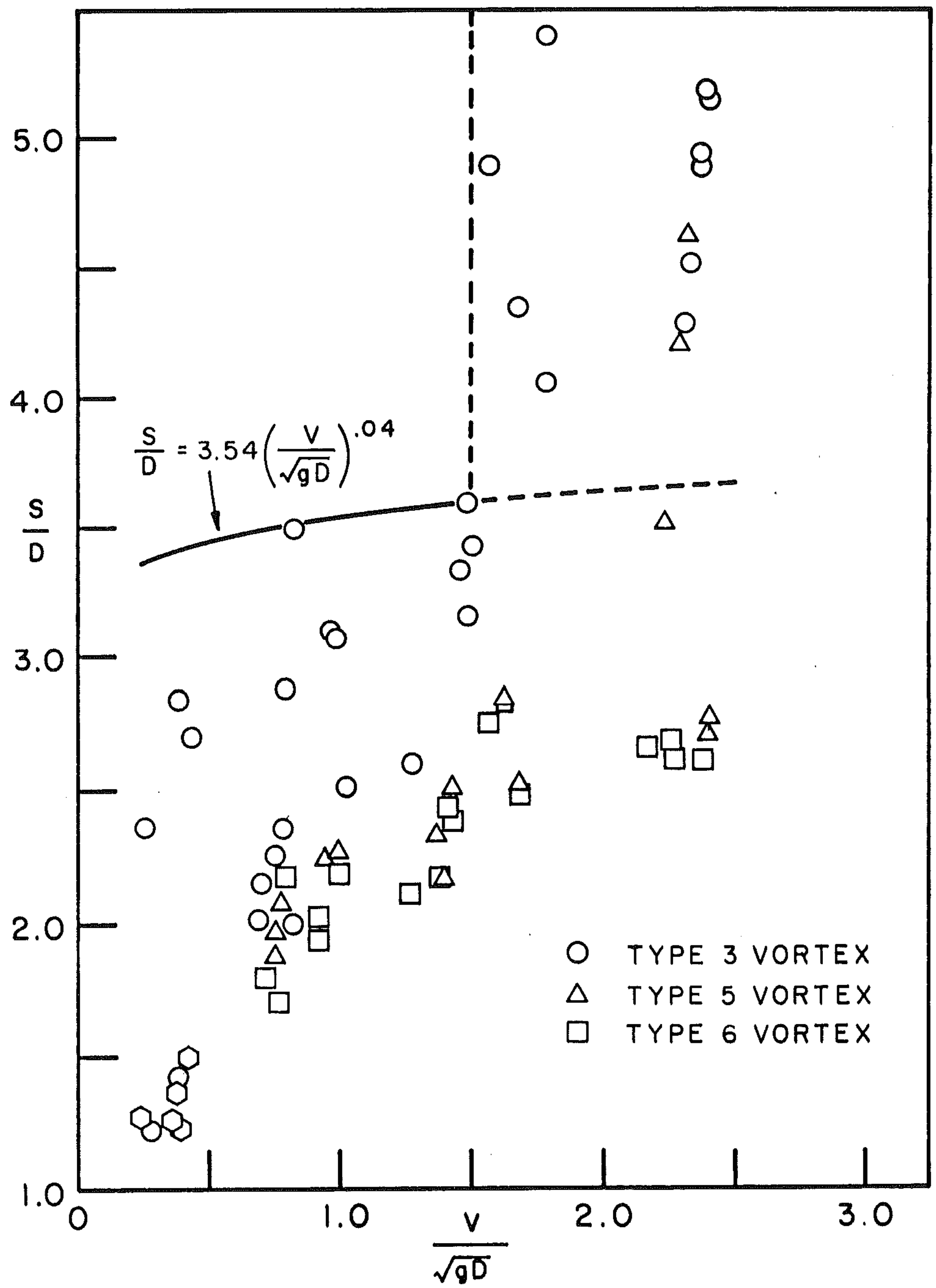

Fig. 36. Dimensionless submergence versus intake Froude number for 15° vane angle and L/W = 3.56. Hexagon symbol indicates viscous dimple.

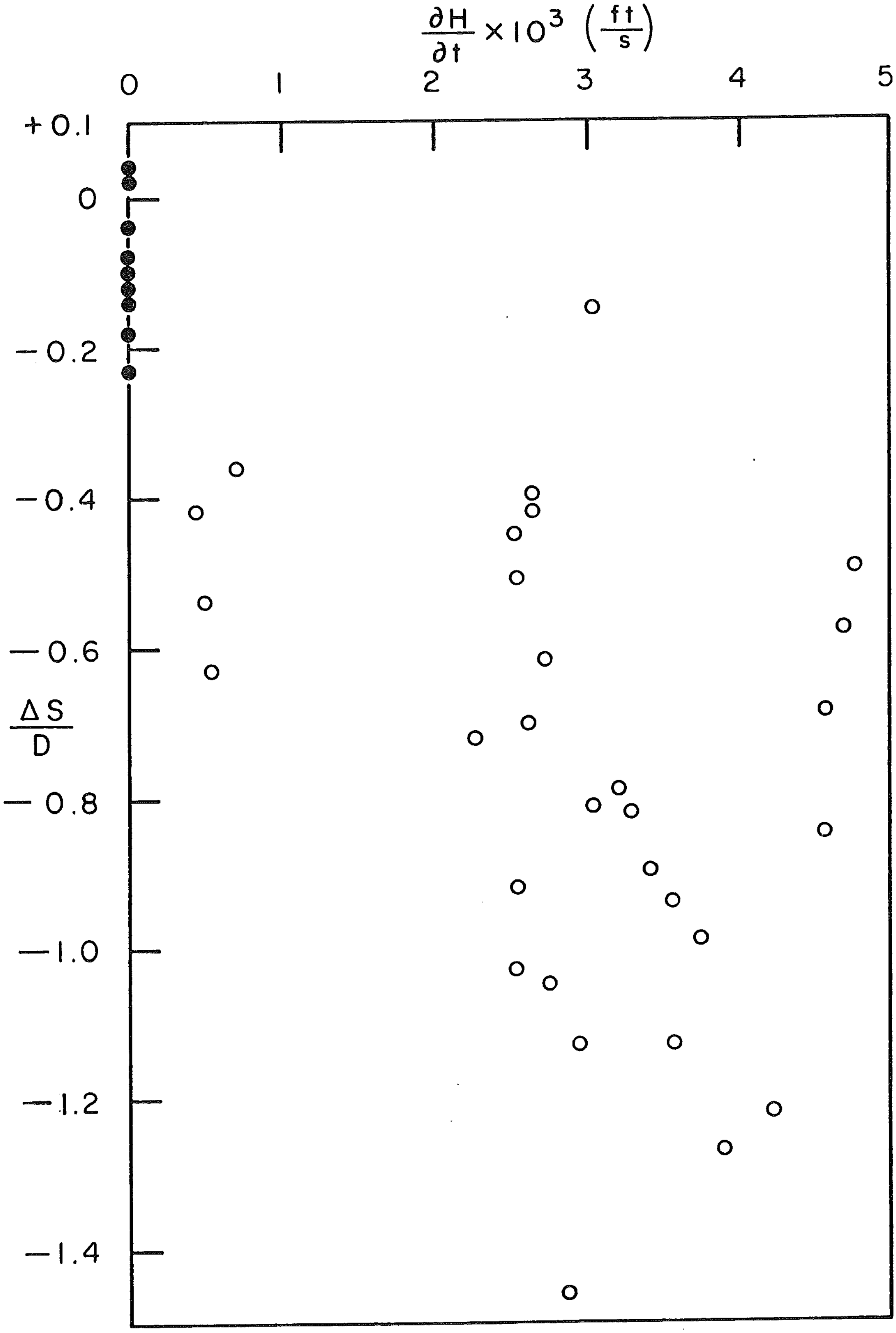

Fig. 37. Difference between actual measurements and envelope curve values of S/D versus rate of change of water surface elevation for Type 5 vortices. Open symbols - "on the run" measurements. Shaded symbold - steady water surface elevation.

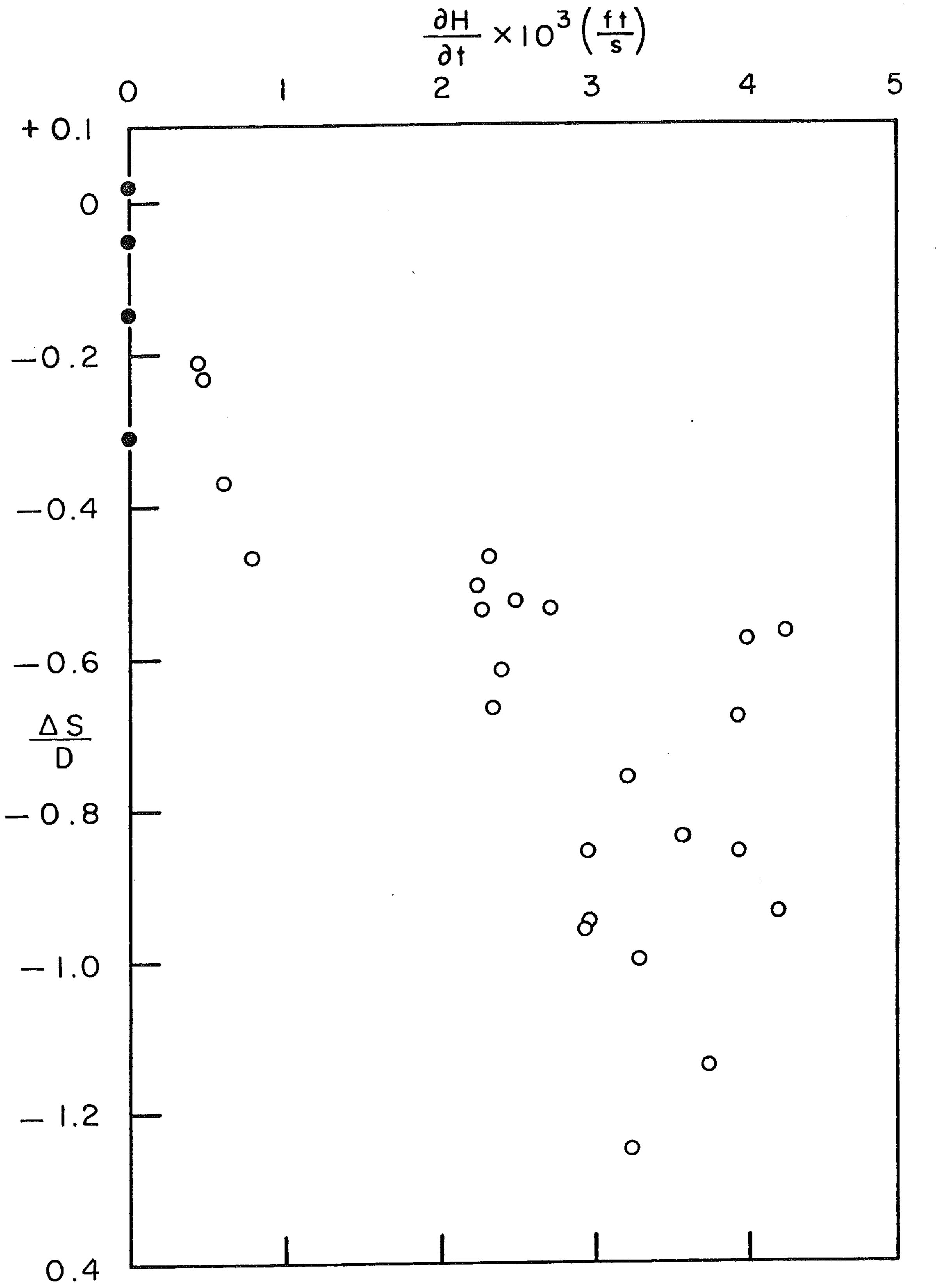

Fig. 38. Difference between actual measurements and envelope curve values of S/D versus rate of change of water surface elevation for Type 6 vortices. Open symbols - "on the run" measurements. Shaded symbols - steady water surface elevation.

These curves dictate the minimum submergence necessary to prevent the formation of vortices at a given intake Froude number for similar approach flow conditions and upstream intake wall lengths. The scatter in the data points below the envelope curves was expected, since many authors' results have indicated this same discrepancy. Thus, the scatter is not specific to these results.

2. Error Analysis

The discovery that the "on the run" measurement technique lead to a consistent error in the critical submergence envelopes for the Type 5 and Type 6 vortices was discouraging, but it does not entirely invalidate the results for these vortex types. An analysis of the 30° vane angle, 6 ft canal wall length data was made to estimate the significance and magnitude of this error.

An envelope curve relating dimensionless submergence and Froude number was drawn for the bubble entraining and the air entraining data points, as shown in Fig. 29. Using these envelope curve relationships, the difference in dimensionless submergence from the calculated envelope curve to the actual data point was calculated, signified herein as $\Delta S/D$. Two plots, shown in Figs. 37 and 38, were made relating the difference in dimensionless stage Δ S/D to the corresponding value of the rate of change of water surface elevation, dH/dt, for bubble entraining and air entraining vortices. From these curves it appears that a relationship between $\Delta S/D$ to dH/dt does not exist for a dH/dt of greater than 2×10^{-3} ft/sec. For a dH/dt of less than 10^{-3} ft/sec, however, the scatter around the line $\Delta S/D$ decreases; finally, at dH/dt= 0, S/D values greater than any of the "on the run" measurements are observed.

Figures 37 and 38 indicate that envelope curves of Type 5 and Type 6 vortices developed from the "on the run" measurements would give S/D values which are between 0.2 and 0.4 less than those of the steady data. These differences are not great considering the nature of the envelope curves and the scatter which exists in both the steady and "on the run" data. Figures 26 through 36 should thus give accurate estimates of critical submergence to avoid Type 5 and Type 6 vortices if between 0.2 and 0.4 is added to the S/D measurements taken on the run. The authors also believe that the envelope curves for the Type 3 vortices in Figs. 26 through 36 are accurate, with no required adjustment due to an unsteady water surface.

An error analysis was also undertaken in an attempt to explain the scatter of the data obtained in Figs. 26 through 36. An estimate of the errors incurred during measurement is necessary as well as the factors which were beyond the control of the research. The primary sources of error were in the measurement of discharge and the water surface elevation at which a particular type of vortex occurred.

There were four sources of error found in the discharge measurement. The first source of error was in the orifice rating curve. This curve was calibrated using the in-house discharge measurement weighing tanks, and estimated to be 0.5 percent. The second source of error was in the reading of the manometer deflection. As was mentioned in the procedure, the supply channel of the water surface elevation was found to be changing with respect to time; this caused the discharge to also change with respect to time. This error was estimated to be ± .04 cfs. Besides the water surface fluctuation, the tank suffered from another error that was not expected. The plywood used in the construction of the tank was found to be of extremely poor quality, which caused the tank to experience premature leaking due to the voids in the plywood. This loss was estimated to be from 0.0 to .02 cfs, since this source of error was always changing with the head in the tank. These were all minor sources of error as compared to the error incurred with the measurement of the discharge removed from storage. This was due to the procedure of taking the data with the stage dropping with respect to time. The change of stage with respect to time was accurate to within ± .002 ft/sec, corresponding to ± .21 cfs in discharge. This results in a total possible error in discharge measurement of ± .21 cfs, an error in the Froude number of ± .27. This error is not significant at the higher values of Froude number, but at the lower Froude numbers it becomes very significant.

There were three sources of error in the stage measurements (water surface elevation). The first source of error was in the measurement of the stage itself. This was found to be ± .002 ft of stage. The second source of error was caused by the wood in the flume, which would swell and contract in conjunction with successive periods of drying and wetting. This swelling and contraction caused the level of the top of the bellmouth to be slightly off, which in turn made the bellmouth lip measurement erroneous. This caused an error estimated at ± .001 ft. There was also a human error in measuring the water surface elevation, estimated to be ± .004 ft. This caused the total error in measurement of stage to be less than ± .005 ft which corresponds to an error of ± .01 in the dimensionless submergence.

Neither the potential errors in discharge or stage could account for the scatter in critical submergence measurements. The change in water surface elevation over time did reduce S/D measurements and add scatter; however, even the steady state data had S/D scatter of ± 0.2. The reason for this scatter is the flow phenomena itself. There is a large range of S/D in which there are two stable forms of flow at an intake with and without a free-surface vortex. The transition between the two is similasr to the transition between laminar and turbulent flow. Some pulse or disturbance must "trip" the straight flow into a swirling flow. If the swirling flow is the more stable of the two states, an even greater disturbance would be required to return to the straight, non-vortex flow. Thus, there are many secondary factors which, within a certain flow region, can cause the swirling vortex flow to begin. These secondary factors cannot be perfectly controlled in any experiment or field installation.

3. Analysis of Results

Envelope curves for the critical submergence required to avoid free surface vortices in the experimental flume are drawn in Figs. 26 through 36. These curves were determined by plotting the data on log-log paper and developing curves such that there were no anomalies between each of the plots, e.g. reducing submergence criteria with increasing approach flow vane angle or with decreasing wall length. It was found that the data was adequately represented when each exponent in the envelope equations were constant for a given wall length. This convention was therefore adopted for simplicity and coherence. The relatively high envelope curve in Fig. 26 is in order to avoid one of the anomolies given above.

At an intake Froude No. greater than 1.5, there appeared to be no submergence which would guarantee vortex-free flow. There is no indication as to whether this is a general phenomena or one specific to the experimental facility. The dashed lines in Figs. 26 through 36 indicate that in the region where $F = V\sqrt{gD} \geq 1.5$, either envelope curve could be correct. The authors are not certain of which.

The envelope curves are tabulated in Table 3 and may be best compared at F = 1.0. These comparisons indicate the following: 1) the submergence required to avoid free-surface vortices increases with decreasing headrace length/width ratio, 2) the submergence required to avoid free-surface vortices increases with increasing approach flow angle, and 3) the headrace length/width ratio becomes increasingly important at larger approach flow angles. This last observation may be seen by comparing envelope curves 9, 10, and 11, and subsequently curves 1, 2, and 3 in Table 3.

Approach flow angle is important because separation around the leading edge of headrace walls will create the circulation required to form a vortex. A long headrace will provide a region for this zone of separation to reattach to the wall, leaving a straight flow approaching the intake, and reducing the tendency for vortex formation.

The envelope equations are valid for intake Froude Numbers as low as 0.25. Below this value the required submergence is assumed to be constant. A further examination of the envelope equations indicates that the dimensionless submergence required to avoid free-surface vortices is greater than 2.0 in all circumstances. This indicates that the data compiled in Fig. 19 may not be entirely applicable to vertical intakes, where $S/D \geq 0.7$ and $F \leq 0.5$ is indicated as a relatively safe region for vortex-free intake operation.

The ultimate purpose of the envelope curves is to develop design criteria for intakes to avoid free-surface vortices. The envelope curves developed herein are not applicable to all intakes but are restricted to intake configurations similar to that of the experimental flume. The intake must be a vertical configuration with an approach channel. The length/width ratio of the channel and the angle of the approach flow into the channel may then be compared with the experimental measurements to find the appropriate envelope curve for critical submergence. Other aspects of the intake, such as bellmouth shape and the channel width/intake diameter ratio, are believed to be less important and should not greatly change the minimum submergence requirements.

If the intake submergence requirements cannot be met, anti-vortex devices must be considered. The type of anti-vortex device which will work for a given intake cannot currently be predicted, however, without a hydraulic model study.

TABLE 3. Envelope Equations for Critical Submergence to Avoid Dye Core Vortices (Type 3) in Experimental Flume

	Approach Flow Vane Angle	Headrace Length/Width	Envelope Equation
1	0°	1.13	$\frac{S}{D} = 3.60\ (F)^{.12}$
2	0°	2.25	$\frac{S}{D} = 3.42\ (F)^{.09}$
3	0°	3.56	$\frac{S}{D} = 2.14\ (F)^{.04}$
4	7.5°	1.13	$\frac{S}{D} = 3.85\ (F)^{.12}$
5	7.5°	2.25	$\frac{S}{D} = 3.45\ (F)^{.09}$
6	15°	1.13	$\frac{S}{D} = 4.16\ (F)^{.12}$
7	15°	2.25	$\frac{S}{D} = 3.99\ (F)^{.09}$
8	15°	3.56	$\frac{S}{D} = 3.10\ (F)^{.04}$
9	30°	1.13	$\frac{S}{D} = 7.00\ (F)^{.12}$
10	30°	2.25	$\frac{S}{D} = 4.59\ (F)^{.09}$
11	30°	3.56	$\frac{S}{D} = 3.54\ (F)^{.04}$

It is apparent that the design criteria developed herein is very limited in application. It is, however, the first experimental program directed specifically towards intake design criteria and should be the beginning of a number of experimental programs on design criteria for horizontal intakes, vertically inverted intakes, further work on vertical intakes, and finally, and on the effectiveness of various anti-vortex devices in each of these configurations. The results of such experimental programs would enable more realistic intake designs, reduce the prevalent need for model studies, and provide basic information on the primary parameters in vortex formation.

V. SUMMARY AND CONCLUSIONS

1. The purpose of the study was to compile and develop intake design criteria to avoid free-surface vortices at hydropower intakes.

2. Literature information on vortex formation at field and model intakes is first compiled and presented to give "intake guidelines" for design engineers. A plot of dimensionless submergence versus intake Froude number is presented for the installations in Fig. 19.

3. The plot is divided into two regions: 1) a region where intake vortices are unlikely and a model study is not required except with extremely poor approach conditions, and 2) a region with a good possibility of intake vortices, where a model study is recommended.

4. Region 2, where intake vortices are a good possibility, is very large, encompassing many hydropower facilities. This is because minimum intake submergence to avoid vortex formation is highly dependent upon approach conditions, which are site specific.

5. In order to add some clarity to this limited design criteria, an experimental study was undertaken which focused upon typical intake approach conditions. Most intakes have a headrace to avoid high circulation near the intake, so the experimental study simulated appraoch conditions with a headrace or approach channel of varying length and width.

6. The experiments were limited to vertical bellmouth intakes. The tendency for vortex formation is enhanced by separation around the leading edge of the headrace channel walls. A long, narrow headrace will reduce the tendency for vortex formation.

7. The headrace length/width ratio is increasingly important with increasing approach flow angle.

8. The submergence required to avoid free-surface vortices was greater than 2.0 for all the arrangements considered. This indicates that the data compiled in Fig. 19 may not be entirely applicable to vertical intakes, which may require a greater submergence than horizontal intakes.

VI. REFERENCES

1. Ables, Jackson H., "Vortex Problem at Intake Lower St. Anthony Falls Lock and Dam Mississippi River, Minneapolis, Minnesota," Tech. Report HL-79-9, U. S. Army Engineer, Waterways Experiment Station, May, 1979.

2. U. S. Army Corps of Engineers, Preliminary Inventory of Hydropower Resources," National Hydroelectric Power Resources Study, Institute for Water Resources, 1979.

3. Rahm, "Flow Problems with Respect to Intakes and Tunnels of Swedish Hydroelectric Power Plants," Bulletin No. 36, Hydraulic Institute, Swedish Royal Institute of Technology, Stockholm, 1953.

4. Jain, A. K., Ranga Raju, K. G., and Garde, R. J., "Vortex Formation In Vertical Pipe Instakes," Proc., ASCE Hydraulic Division, Vol. 104, No. HY10, Oct., 1978.

5. Sweeney, Charles E., Elder, Rex A., and Duncan, Hay, "Pump Sump Design Experience: Summary," Proc., ASCE Hydraulic Division, Vol. 108, No. HY3, March, 1982.

6. Daggett, Larry L. and Keulegan, Garbis H., "Similitude in Free-Surface Vortex Formations," Proc., ASCE Hydraulic Division, Vol. 100, No. HY11, Nov., 1974.

7. Anwar, H. O., "Formation of a Weak Vortex," Journal of Hydraulic Research, Vol. 4, No. 1, 1966.

8. Anwar, H. O., "Measurement of Non-dimensional Parameters Governing the ONset of Free Surface Vortices--Horizontal and Vertically Inverted Intakes," Hydraulic Research Station, Wallingford, England, Report No. IT 216, Aug., 1981.

9. Amphlett, M. B., "Air Entraining Vortices at a Vertically Inverted Intake," Hydraulic Research Station, Wallingford, England, Report No. OD 17, Sept., 1978.

10. Yildirim, N. and Jain, S. C., "Surface Tension Effect on Profile of a Free Vortex," Proc., ASCE Hydraulics Division, Vol. 107, No. HY1, Jan., 1981.

11. Zielinski, Paul B. and Villemonte, James R., "Effect of Viscosity on Vortex Orifice Flow," Proc., ASCE Hydraulics Division, Vol. 94, No. HY3, May 1968.

12. Hebaus, George G. Discussion of "Vortex Formation at Vertical Pipe Intakes," Proc. of ASCE Hydraulic Division, Vol 105, No. HY10, Oct., 1979.

13. Anwar, H. O., Weller, James A., and Amphlett, Michael B., "Similarity of Free-Vortex at Horizontal Intake," Jour. of Hydraulic Research, Vol. 16, No. 2, 1978.

14. Prosser, M. J., "The Hydraulic Design of Pump Sumps and Intakes," BHRA Fluids Engineering, Cranfield, Bedford, England, July, 1977.

15. Gordon, J. L., "Vortices at Intakes," Water Power, April, 1970.

16. Reddy, Y. R. and Pickford, J. A., "Vortices at Intakes in Conventional Sumps," Water Power, March, 1972.

17. Humphreys, Harold W., Sigurdsson, Gunnasr, and Owen, James H., "Model Test Results of Circular, Square, and Rectangular Forms of Drop-Inlet Entrance to Closed-Conduit Spillways," Illinois State Water Survey, Urbana, Report of Investigation 65, 1970.

18. Pennino, Bruce J. and Hecker, G. E., "A Synthesis of Model Data for Pumped Storage Intakes," ASME Fluids Conf., Chicago, 1980.

19. Denny, D. F. and Young, G. A. J., "The Prevention of Vortices and Swirl At Intakes," British Hydromechanics Research Association, Harlow, Essex, England, Proc. 7th General Meeting IAHR, p. G1-G1-16, 1957.

20. Ziegler, E. R., "Hydraulic Model Vortex Study Grand Coulee Third Powerplant," REC-ERC-76-2, Engineering Research Center, Bureau of Reclamation, Denver, CO, Feb., 1976.

21. Blaisdell, Fred W., "Hydraulics of Closed Conduit Spillways: Parts II through VII; Results of Tests on Several Forms of the Spillway," Tech. Paper No. 18, Series B, University of Minnesota, St. Anthony Falls Hydraulic Laboratory, March, 1958.

22. Gwinn, W. R., "Tests of Steel Deck Grating for Vortex Suppression on Closed Conduit Spillways," Research Report NO. 316, Stillwater Outdoor Hydro. Lab., Stillwater, OK., Dec., 1958.

23. Song, Charles C. S., "Hydraulic Model Tests for Mayfield Power Plant," Project Report No. 148, University of Minnesota, St. Anthony Falls Hydraulic Laboratory, April, 1974.

24. Hecker, George E., "Model-Prototype Comparison of Free Surface Vortices," Proc., ASCE Hydraulics Division, Vol. 107, NO. HY10, Oct., 1981.

25. Durgin, W. W. and Anderson, F. A., "Davis Pumped Storage Project Hydraulic Model Studies; Intake Model, Upper Storage Reservoir," Alden Research Laboratories, Worcester Polytechnic Institute, Holden, Mass., Oct., 1972.

26. Blaisdell, F. W. and Donnelly, C. A., "Hydraulics of Closed Conduit Spillways: Part X, The Hood Inlet," Technical Paper 20, Series B, Agricultural Research Service, St. Anthony Falls Hydraulic Laboratory, 1958.

27. Rhone, T. J., "Hydraulic Model Studies of the Spillways and Outlet Works--Glen Canyon Dam--Colorado River Storage Project, Arizona," Hydraulics Branch Report No. HYD-469, Bureau of Reclamation, 1964.

28. Bucher, K. G., "Hydraulic Model studies of the Oroville Dam Powerplant Intake Structures," Hydraulics Branch Report HYD-509, Bureau of Reclamation, 1965.

29. Colgate, D., "Grand Coulee Pumping-Generating Plant Model Studies, Conduit Entrances P.G7 & P/G8," GR-80-4, Hydraulics Branch, Division of Research, Bureau of Reclamation, 1980.

30. Johnson, P. L., "Hydraulic Model Studies of the Intake and Suction Tubes for Havasu Pumping Plant," GR-19-76, Hydraulics Branch, Engineering and Research Center, Bureau of Reclamation, 1976.