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# INVESTIGATION OF DISCHARGE THROUGH GRATED INLETS

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16. Abstract

An experimental investigation of the hydraulic performance of grated inlets under sump conditions is reported. Measurements of the discharge coefficient for orifice flow were made for reticuline grates, slotted grates, and crossbar grates. The effect of trash was examined. Measurement of flow losses were made for the same three grates under a full flow condition. Performance of the reticuline grate exceeds that for the slotted grate for both conditions.

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## U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

| MULTIPLY | BY | TO OBTAIN |
|---|---|---|
| inches | 2.54 | centimeters |
| feet | 0.3048 | meters |
| square inches | 6.4516 | square centimeters |
| inches/second | 2.54 | centimeters/second |
| feet/second | 0.3048 | meters/second |
| cubic feet/second | 0.02831685 | cubic meters/second |
| pounds (mass) | 0.4535924 | newtons |
| pounds (force) | 4.448222 | newtons |
| kips (1000 pounds) | 4448.222 | kilograms |
| pounds/sq. inch | 6894.757 | pascals |
| pounds/cubic foot | 16.0185 | kilograms/cubic meter |
| tons/square foot | 9764.86 | kilograms/square meter |
| kips/square inch | 6894757 | kilopascals |

# SUMMARY

This report is concerned with the hydraulic performance of vertical drains for ditch bottoms covered with gratings for entrance protection. These inlets act much like common culverts in that the performance may be controlled or limited by various geometrical factors, drainline dimensions and tailwater stage. Several flow regimes may exist, including weir flow, outlet controlled flow and inlet controlled flow. Under inlet flow conditions, the flow limitation is due primarily to contraction effects, while for outlet control losses along the path act to reduce the flow rate. The presence of a vortex over the inlet may exert substantial influence on hydraulic performance, not only as a flow limitation but also as a mechanism for trash accumulation.

The purpose of this study is to determine whether the addition of a grating causes substantial alteration in the performance of the drain. The grating serves several purposes including safety and exclusion of trash from the downstream components of the drain structure. Unfortunately, since the grate is the same size as the entrance and located at a point of high velocity, trash accumulation problems are worsened.

Experiments were conducted as follows:

1. The discharge coefficient for inlet control both with and without gratings was measured. Three different grating designs (reticuline, crossbar, slotted) were tested and compared to an entrance with no grate. Since the presence of residual circulation in the pond may influence the formation and strength of the drain vortex, conditions of both suppressed circulation and stimulated circulation were examined.

2. A brief examination of the influence of trash accumulation as well as surrounding roughness elements was made under conditions of inlet control.

3. The loss coefficient for the grating was deduced by comparison of the discharge with and without gratings under conditions of outlet control. The grating was observed to have a strong influence on air aspiration, leading to poor performance under some conditions.

The results of this investigation show that the reticuline grate performs well. Coefficients of discharge and loss factors for grates tested are summarized as design data.

# INTRODUCTION

Inlet structures are employed to convey water from an open reservoir. Usually the structure comprises the entrance treatment and a drainline connection to the downstream receiving water. Flow at the entrance is complex, being in part influenced by the free surface condition and in part by the development of pressure flow downstream. Inlets are frequently found in conjunction with storage reservoirs, detention ponds, hydroelectric power plants and pumped storage.

The focus of this study is the performance of drains installed in ditch bottoms for roadway applications (for example, State of Florida, Roadway and Traffic Design Standards, Index 232, without slot) and operating under sump conditions. These drains consist of a horizontal flush inlet set over a vertical drop box. The purpose of this investigation is to provide comparative performance data for gratings used to cover the entrances to these inlets. Failure to properly design drainage structures can increase the risk of flooding property that is upstream of the structure. In many cases it may be difficult to predict reliably what conditions may exist at either the entrance or the exit of the structure. Thus, it is important to understand what the minimum performance is likely to be. Of particular interest is the reticuline grating, originally designed as "bicycle safe" and often used in streets and other circumstances where bicycle traffic is probable. Reticuline grates are constructed from a series of parallel bars set on edge. The spaces between the bars are filled with another bar, bent periodically at angles to form a zigzag pattern, serving as reinforcement and also to make the opening small for safety. The grate is banded at the outside to form a unit. The net result is a grate with large open area but also segmented into a number of small openings.

Figure 1 shows an example of a reticuline grate and a slotted grating for comparison. The reticuline grate is installed in a ditch bottom to cover a flush inlet. While in the past, several studies focused on gutter flow conditions [1,2], less attention has been given to performance under sump conditions with possible high heads. Entrances formed by drop boxes used as detention control structures are also sometimes covered by grates to provide protection and emergency overflow, however this inlet type is not flush, but stands up from the pond bottom to form a reentrant entrance. While performance may be similar, this configuration was not investigated here.

Possible factors influencing the hydraulic performance of the inlet with grating include:

1. The hydraulic regime of operation of the structure

2. The geometry of the grating

3. The presence of a vortex

4. The accumulation of debris at the grating

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This report comprises an examination of each of these factors and an experimental investigation of the alteration of performance induced by several grate types.


HYDRAULIC PERFORMANCE OF INLET STRUCTURES

In contrast to the physically large intake structures that can serve as suction lines for pumps or turbines, the horizontal grated inlet of interest here is a small, gravity driven structure that may be compared to a conventional culvert. In 1958, Blaisdell [3] reported an extended study of inlets associated with closed conduit spillways. This study was followed by an extended investigation of inlets in 1970 by Humphreys, et. al. [4]. The overall performance of the intake structure is often represented on a head-discharge diagram as shown schematically in Figure 2. Performance may be viewed as the locus of all possible operating states for the complete structure. Usually, the head represented in this diagram is the submergence head, defined from the entrance elevation.

An extensive review of the literature was conducted to provide background information for this study. Similar, related applications include drains in parking lots and outfalls from detention ponds. Although hydropower installations are not of interest here, there is a considerable body of literature concerning these installations which have equal relevance to gravity drains. Consequently, the discussion below includes numerous references in this area.

For purposes of this discussion, it will be assumed that sump conditions (no organized flow) exist in the upstream ponding. As in the case of culvert performance, several different flow regimes may be observed at the inlet, each governed by different control or flow limitation. At the lowest head, the flow regime is weir flow with only partial coverage of the entrance. Depending on geometrical factors at the inlet, this flow may resemble a free overfall, or if a grate is present the flow pattern may be more complicated. In this regime, a small increase in head results in a large change in flow capacity. As the head rises, however, the entrance floods and the flow begins a transition to a different operating regime. In some cases the structure fills with water completely (ie. primes) and full flow develops. Control results from the tailwater or conditions in the barrel draining the box. Because the box itself constitutes a short nozzle, a regime of operation with the box flooded (but not the barrel) could result. While possible, this mode is not likely in applications of interest here since drop box heights are not great [5]. Alternatively, the control point may remain at the inlet entrance, in which case the flow is a true orifice flow. The differences between full flow and orifice flow are illustrated in Figure 3.

It is important to recognized that the flow can be governed by different elevations, depending on the circumstances of control. For inlet control the appropriate head is the submergence measured from the inlet, assuming that the receiving box is at atmospheric pressure. If the box does not communicate with the atmosphere, it is possible that the pressure in the box may be different than atmospheric resulting in a different flow rate. When priming occurs, the lower elevation controlling the flow is farther downstream, possibly at the entrance to the drainline or at the tailwater. Thus, even though the

performance map is usually presented in terms of the submergence head, once the drain primes, the flow rate is governed by elevational differences other than the submergence.

Fundamental distinctions separate a true orifice flow from other types of inlet flow. For an ideal orifice consisting of an aperture in a thin plate and exhausting freely at atmospheric pressure, the submergence head drives the flow and the liquid is accelerated to pass through the orifice. For much of the distance traversed to the orifice, the flow velocity is relatively small. Losses, which are proportional to the kinetic energy are small also. However, as the body of the flow leaves the plate, a distinct contraction develops due to flow separation. Assuming that the ambient pressure is constant for discharge and that no flow obstruction is present, only the upstream conditions and the contracted area of the flow affect the efflux.

In contrast to orifice flows, other types of intake flows include short nozzle extensions or situations where the entrance is directly connected to a pipe downstream of the inlet at the reservoir. In typical installations of interest in this investigation, the opening is located over a drop box serving as a transition to the drainline. The drop box may be viewed as a nozzle extension. In this circumstance, the driving elevational difference is determined by the elevation at the end of the pipe or if the discharge is to a reservoir, the tailwater elevation. The flow may be substantially influenced by conditions downstream including frictional effects. In this case, the inlet structure may be viewed as a transition from a free surface flow to a pressure flow. Additional hydraulic losses may be incurred by the installation of a grate at the entrance.

Depending on geometry and other factors, circulation often develops and strengthens above the inlet to become a vortex, dominating the flow, both for inlet and outlet control situations. Only distributed vorticity from boundaries or discrete vortices shed by nearby objects form stable vortices over the inlet. Figure 4 shows the stages of vortex development. The weakest condition is the development of surface swirl, which progressively grows to a surface dimple. Trash and floating debris are sucked into the inlet with further strengthening. The strongest condition is the development of an air entraining vortex over the inlet.

Drain vortices have been extensively studied. Fundamental analytical [6-10] and experimental studies [11-15] have been conducted to clarify the formation and structure of vortices. At least two review discussions have been presented [16,17]. Of particular interest here are several studies of the formation of vortices over inlets [18-27]. The design of inlets and the problems associated with vortex formation have been recently reviewed and summarized [28]. Numerous model studies have been conducted to investigate specific installations [29-32] and several methods for suppressing vortices have been proposed and tested [33-36].

Several issues emerge as important to this investigation:

## Critical submergence

The height of the water above the inlet plays an important role in determining the surface flow characteristics. Both in the case of orifice flow and also when the structure primes, vortices can develop at the inlet. Usually, air core vortexes persist until the head is substantially above the inlet. This critical submergence is of the order of several hydraulic diameters, but may also be influenced by the presence of solid boundaries [32]. Conversely, a minimum depth is required before the weir regime ceases and the inlet is flooded with water. Between these states, a region of vortex flow is likely, with both transient and steady vortices appearing. Most inlets of interest here may operate in this range. Evidence of vortex formation can be seen almost as soon as the inlet is fully covered, and even at higher heads the inlet is not submerged to a depth sufficient to totally eliminate the vortex. Thus, air and trash entrainment are characteristic of typical installations.

At question here is the effect that the presence of a vortex may exert on the hydraulic performance of the system. If a vortex forms over an inlet, reduction in flow rate can be expected. In the case of orifice flow, discharge is decreased because the air core reduces the effective area of the inlet and also because the kinetic energy of the swirling component of the flow can increase flow losses. In fact, flow reduction due to vortex formation has been used to advantage in dropshafts and several other devices designed to regulate inflow quantities to some intakes [37-46]. If the inlet is operating under conditions of full flow, the swirling motion induced in the drain line may add substantial hydraulic losses to the system as well as altering the inlet flow development. As discussed below, interaction of the vortex with any grating added to the inlet may be anticipated.

Unsteady discharge may also result from vortex development. Air entrainment at the inlet may dramatically affect the overall performance of the system by binding or partially blocking the flow [47,48]. Such action can cause the system to develop long term oscillatory behavior as air is taken into the system, builds up to retard the flow and then is disgorged to continue the cycle. Even transient eddies that do not develop into permanent air cores can rapidly strengthen as they are pulled into the system and cause temporary reduction in flow [33].

## Vortex suppression

Because of the many deleterious effects of vortices at inlets, considerable effort has been expended towards developing effective suppression. Redesign of the inlet to include floating rafts, covers, and hoods has been advocated as well as vertical walls or vanes, positioned either across the entrance or at the side [5]. Depending on circumstances, all of these methods are useful, however the fact that air entrainment is no longer apparent does not mean that the vortex has been suppressed. Trash may still be entrained.

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## Grates and screens

Examination of the literature [21,33,36,47] indicates that grates can have both negative and positive influence on the hydraulic performance of the entrance assembly. Aside from additional losses added to the flow path [29,32,51], the net effect depends on three factors:

1. Opening ratio
2. Antiseparation effects
3. Trash accumulation

In patterns such as the reticuline design, the grating converts the entrance into multiple small openings in close proximity to one another. Thus the total discharge is the sum of many small but possibly interacting passages. For gratings with relatively large area fractions, the principal effect may be to reduce separation and straighten the flow. Under some conditions performance may be enhanced.

A common thread in many investigations is the observation that trash racks or screens may serve to suppress or mitigate vortex development by interfering with the circulation [21,26,29]. A screen or grate does not need to cover the entrance but may be located so that tangential flow is reduced. If flow passes through the openings, the thickness must be relatively large to obtain flow straightening. In at least one case [32], a vortex suppressor was installed as a trash rack. A dual purpose application is not of particular interest here, however.

## Debris accumulation

Although a highly variable factor, the effect of trash must be considered. The accumulation of debris may be limited to an area blockage effect or may influence the flow development. All types of inlet structures are plagued by blockage caused by the accumulation of trash and debris [22,26,31,50]. In an attempt to alleviate the obstruction of the conduit downstream of the inlet, screens and grates are added to the structure, however the screen itself can be blocked and ultimately develop as the controlling point in the flow path. The effect of accumulation on a grate or screen is twofold; the area of the flow is reduced and also additional contributions to hydraulic losses are introduced.

Under almost all conditions, trash and debris are entrained by the local acceleration of the fluid approaching an inlet [49]. As submergence increases and a vortex develops, buoyant debris is entrained and to some extent concentrated in the swirling flow surrounding the inlet. Depending on the strength of the vortex, some of this material is sucked down to the inlet face. Because the trash is only modestly different from the water in density compared to air, this action occurs even before an air core develops (Figure 4).

In contrast, since the bottom flow field of a vortex remains radial, trash that sinks to the bottom moves directly to the inlet. There is some evidence that the presence of a

large raft of floating trash centered in a vortex may actually act as a suppressor [33]. Likewise bottom roughness may restrict the motion of trash along the bottom.

## Proximity

For completeness, the interaction between two inlets sited close together was considered. There are relatively few literature references to this problem, but it has been examined in relation to multiple power plant intakes [29]. It is to be expected that the flows will influence each other to some extent [33], and especially two vortices can interact, travel together [23], or merge to become one.

## EXPERIMENTAL INVESTIGATION

As stated previously, the principal objective in this study is not to document the overall performance of a particular structure, but rather to obtain information concerning the influence of gratings on the performance of inlets. In order to better understand the reticuline grate (shown in State of Florida, Roadway and Traffic Design Standards, Index 232), which is of most interest here, measurements of two other grates were obtained for comparative study. One of these grates was the cast grate, slotted with a relatively small open area (also shown in Index 232). The second was a grating consisting of straight bars joined by round cross bars (Index 219).

Two types of experimental measurements, corresponding to inlet and outlet flow regimes, were undertaken during this investigation. First, the discharge coefficients for grated inlets were examined under orifice conditions, with no pressure gradient across the orifice. This situation is typical of an inlet placed on top of a drop box that is at atmospheric pressure, perhaps because the outlet pipe is not flowing full or because the box is vented to the atmosphere. Under these conditions, changes in pressure in the box that could affect the flow rate are avoided. Second, a separate experiment was conducted to measure the hydraulic losses for full flow conditions. These two experiments are explained in more detail below.

The experimental facility used in this investigation was originally developed for an investigation of culvert endsection performance. The facility comprises two large fiberglass tanks (6x6x12 feet) connected by a 10 inch PVC drain line. One tank acts as a sump and the other as a supply reservoir. Models for testing are set in the supply tank. Water is circulated by means of a 4 inch variable speed pump, another 4 inch pump and a 6 inch pump. The tanks are baffled to prevent air recirculation. Flow is measured by calibrated electronic paddlewheel flow meters in each supply line. Calibration of these flowmeters has been developed by using thin plate weirs. Head is measured by a piezometer connected at the far end of the supply tank. Height in the supply tank was measured by means of a standpipe and height gauge with a minimum resolution of .003 feet. A similar measurement was used when the elevation of the water level in the sump was required.

Because of the limited size of the facility, it was necessary to test the model gratings and inlets on a one-quarter scale. This technique is commonplace for inlet testing and is especially well developed for hydroelectric and other powerplant intakes, although small models are generally used. Here the scale ratio of the inlet model is closer to full size and quite comparable with other gravity inlet studies [3]. In addition to many of the references listed above, the scaling of vortices at inlets has been discussed in References [50,52-60]. Many investigators have found that the behavior of the vortex in scale models may be less intense that in the prototype, especially where large ratios are used [28]. Similarly, weir flow across gratings may not scale well [61].

As stated previously, reticuline grates were the primary focus of this study. A 1:4 model of the reticuline grate was constructed from .05 inch brass sheet stock. The dimensions of the bar stock used in the prototype were closely matched but since all components of the model were of the same thickness slight dimensional discrepancies were tolerated. The reticuline model was assembled according to standard dimensions. For comparative studies, a model slotted grate was machined from aluminum in the same scale. Finally, for further comparison, a cross bar model grating was constructed on the same scale as the reticuline and slotted grates. In this case the overall dimensions were not matched but the grate spacing and dimensions were held to the same scale, since the typical proportions do not match the other two grate types. Thus comparisons were limited to the pattern of the grate. The following scale relations apply to all models:

| DIMENSION | RATIO | SCALE RELATION |
|---|---|---|
| length | $L_r = L$ | 1:4 |
| area | $A_r = L^2$ | 1:16 |
| velocity | $V_r = L_r^{1/2}$ | 1:2 |
| discharge | $Q_r = L_r^{5/2}$ | 1:32 |

Surface roughness was not scaled. The prototype surface was assumed to be metal and the box assumed to be finished concrete. The grate models were metal and the wood portions of the inlet were resin coated and painted.

The appropriate nondimensional parameters are:

the Weber number:

$$We = V\sqrt{\frac{\rho d}{\sigma}}$$

the Reynolds number:

$$Re = \frac{Vd\rho}{\mu}$$

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the Froude number:

$$Fr = \frac{V}{\sqrt{gd}}$$

and the Kolf number:

$$Ko = \frac{\Gamma}{Vd}$$

In these parameters $\rho$ is density, $\sigma$ is surface tension, $\mu$ is viscosity and $\Gamma$ is circulation. V and d are a characteristic velocity and linear dimension, respectively. Using a characteristic velocity of 5 feet/second and a linear dimension of 1 foot gives a Reynolds number of $10^6$, a Weber number of 30 and a Froude number of 0.6.

The conclusion of several studies [24,28,53] is that surface tension effects are minimal, especially for the conditions encountered in the experiments reported here. It is possible to define a Reynolds Number based on either the radial velocity towards the inlet or a tangential velocity. Like surface tension, viscosity is not likely to be an important parameter here due to the limited range of variation and the large Reynolds number [62].

Two Froude numbers can be also defined, one based on submergence and another based on the diameter of the inlet. A common practice is to report the performance of a specific structure in terms of a modified Froude number based on a characteristic orifice dimension [3]:

$$Fr = \frac{Q}{D_H^{\frac{5}{2}}\sqrt{2g}} \tag{5}$$

There is no guarantee however, that Froude modeling will correctly predict every feature of the prototype from model studies. Finally, the circulation was not modeled or measured in this experiment rather several circulation conditions were tested in the manner of Reference [4].

## MEASUREMENT OF THE DISCHARGE COEFFICIENT FOR INLET CONTROL

To examine inlet discharge, a drain box (1.67 feet wide, 2.58 feet deep, 2.5 feet long) was constructed with a horizontal plate (4x4 feet) mounted on top. A rectangular opening with a lip corresponding to typical box specifications was cut in the center of the plate so that a flush, horizontal configuration was simulated. To ensure that the box was at atmospheric pressure, a horizontal 1-1/2 inch clear PVC pipe was installed in the side of the box below the plate. This pipe was led to the back of the tank to a riser open to

the atmosphere. While experimental measurements were being made the horizontal portion of this pipe was monitored for the presence of water which would indicate that the box might not be at atmospheric pressure. Because the grate was located relatively high in the tank, the available head was limited to about 1 foot (corresponding to 4 feet in the prototype).

All testing reported here was conducted under conditions of minimal approach flow, nominally sump conditions. This does not mean however that the water was quiescent. Usually during a run, residual swirling motion and some currents were observed in the head tank (in fact merely turning on a different pump caused some fluctuations, including vortex reversal). This circumstance is not unlike that found in the field. While runoff may be ponding above the inlet, it is not expected to be completely motionless and some circulation may develop. It is not realistic to hope that the designer can predict the circulation transported to the inlet in a specific installation.

This initial circulation is due to geometrical elements such as walls and protruding elements and will eventually become the standing vortex as water is drawn into the inlet. Consequently, it was decided to examine three cases, a) "free" approach, b) suppressed circulation, and c) deliberate introduction of circulation. Each of these circumstances is shown in Figure 6. No modifications were made to the facility in order to investigate a free approach. Two methods were used to suppress the residual circulation present in the head tank. In one case, an array of radial guide vanes were place around the inlet and surrounded by a porous media in order to quiet the flow approaching the inlet. For comparison, some measurements were also made by using a vertical wall located close to the inlet for suppression of the inlet vortex (see for example Index 235, State of Florida Roadway and Traffic Design Standards). To stimulate a stronger vortex over the inlet, a sharp edged obstruction was placed in the path of the flow approaching the inlet. A strong vortex is shed from this edge and captured by the inlet [4].

The measurement of flow rate as a function of submergence head can be used to compute a discharge coefficient according to

$$Q = C_D A_{act} \sqrt{2gh} \tag{6}$$

The area $A_{act}$ is the actual open area of the aperture, a dimension that requires some interpretation. While the nominal grate opening is .44 square feet, there is a small lip to support the grate, reducing the area to .32 square feet. In the case of the slotted grate, the lip does not overlap the open area of the grate but does when the reticuline grate is installed. For all grates, only a fraction of the area is actually open, as shown in Table 1, which also shows the actual area used to compute the discharge coefficient.

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The hydraulic diameter of the opening is defined in terms of the nominal area $A_{nom}$ and the perimeter P of the opening.

$$D_H = \frac{4A_{nom}}{P} \qquad (7)$$

Introducing the hydraulic diameter into Equation 6 yields

$$\frac{Q}{D_H^{\frac{5}{2}}\sqrt{2g}} = C_D \frac{RA_{nom}}{D_H^2}(\frac{h}{D_H})^{\frac{1}{2}} \qquad (8)$$

where

$$R = \frac{GRATED\ AREA \times AREA\ FACTOR}{NOMINAL\ AREA} \qquad (9)$$

The discharge coefficient is plotted as a function of the ratio of submergence head to hydraulic diameter ($D_h = 0.656$ feet) in Figures 7-11. Typically, this relationship consists of a steep rise in discharge coefficient corresponding to weir performance, a transition zone, then a relatively constant branch representing orifice performance. The vortex developed almost as soon as the entrance was flooded and was always present for greater submergence. When the radial suppressor was used, the vortex could be quite weak or transient. For completely free discharge, the direction of the vortex and the discharge coefficient were sensitive to pump start up, indicating that stray circulation may cause deviations in performance. All other configurations appeared to suppress this effect.

A straight line has been added to the region of relatively flat performance to provide an estimate of the discharge coefficient suitable for general design purposes. It is emphasized that this line does not represent a computed fit to the data and that it encompasses all circulation conditions tested, except the vortex intensifier. The results are summarized in Table 1.

Another experiment was conducted to compare the performance of the crossbar grating to that of the reticuline grating. Because the geometrical characteristics are comparable (Table 1), the purpose of this experiment was to eliminate the effect of the complex configuration of the reticuline grate. Tests were conducted only under free approach conditions. As shown in Figure 10, comparable performance was obtained, which indicates that the high performance level observed is likely to be due to the similar open configuration, many small openings separated by vertical bars.

Several supplemental experiments were conducted. Figure 11 illustrates the effect of trash. In this case the "trash" consisted of a metal plate laid diagonally across the opening to obscure one-half of the effective area. In one case, during an experiment

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with a radial suppressor in place, it was observed that even a small amount of trash could stimulate the vortex to strengthen. An experiment to examine the effect of bottom roughness was conducted using a sheet of air duct filter material on the horizontal surface. No significant effects were noted and this experiment was not pursued. It is noted however, that Anwar [35] has observed that bottom roughness can reduce radial flow toward the entrance. Thus some control of submerged trash may be possible through the use of bottom roughness elements.

## MEASUREMENT OF THE LOSS COEFFICIENT AT FULL FLOW

The purpose of the second type of experiments was to determine entrance losses for the grate when the inlet is completely flooded, with the box and drainline primed. Measurement of loss coefficient under full flow conditions was conducted by constructing a mounting for the grate using a 10 inch PVC elbow with a small box covered by a horizontal plate added to the top of the elbow to simulate a flush entrance. Since the only parameter of interest was the loss coefficient of the grate, no effort was made to model the drop box but rather only to ensure the full flow condition. All experiments were conducted as free flow towards the inlet, and no vortex suppressors were employed. Measurements of head and discharge were made as before, with the outlet pipe flowing full and submerged.

Often, turbulent losses for hydraulic components are correlated with the velocity head (square of the flow rate). Thus

$$h_L = K \frac{V^2}{2g} \qquad (10)$$

For design purposes, the loss factor K, is assumed to be approximately constant with flow. The loss factor may not actually be constant with submergence depth or velocity, because a vortex may be present and altered by the grate. Summing losses from the head tank to the sump and applying Bernoulli's equation

$$h - h_{sump} = \sum_i h_{Li} \qquad (11)$$

The effect of placing a grating over the inlet is to add another loss term. Assuming that all other losses remain the same at the same flow with or without the grate, the loss due to the grate can be calculated by comparing the elevational difference measured at the same flow with and without the grate.

Unlike orifice flows, when full flow (outlet control) is established for the intake, it is possible to vary the submergence depth and flow rate independently. During a test, a constant head was maintained in the reservoir and the flow rate was varied by changing the sump elevation. A comparative series of experiments were conducted by first measuring the discharge as a function of head differential when no grate was installed and then performing the same experiment with a grate present. In this manner, the inlet

loss factor due to the grating can be determined by subtracting the sum of losses without the grate from the total losses with the grate present.

When no grate was present, a relatively stable vortex was observed and while a straight line correlation was not obtained, a loss coefficient could be estimated (Figure 12). When the grating was inserted in the inlet, however, similar results were obtained only for very low flow rates (Figure 13). Instead of the expected behavior, an early transition from one type of operation to another was observed. In order to maintain a constant submergence depth as the flow rate increased, a substantial change in driving head was required. Before this transition occurred the trend of the data was as expected.

The observation that a flow transition did not readily occur when the inlet was open led to the conclusion that the vortex interacts with the grate to promote air binding. This condition is common in many low pressure lines and often plagues culvert installations. One possibility is that the tip of the air core penetrates the grate and breaks up into many smaller air bubbles. These bubbles are easily dragged into the line to accumulate, since the breakup occurs near the point of highest velocity (Figure 14). A large air bubble forms and is stabilized by drag forces, causing increased losses.

As a solution to the problem, it was found that venting the portion of the drainline immediately downstream of the elbow supporting the intake relieved the problem (as shown in Figure 13). Venting produced little effect on performance when the inlet was open, although the data were more uniform (Figure 12). Sudden transitions were still observed with venting but the flow rate at which these occurred was much higher. Presumably, when vents were opened, air blockages, either in the drainline or the box beneath the grate, did not occur until higher flow velocities were developed. Some conditions produced large scale oscillations in the supply and sump tank and were excluded as not representative of the steady state full flow regime.

Experiments conducted with a vented line permitted the computation of the loss coefficient for the grating as discussed above. Three different submergence heads were examined. Figures 15-18 show the correlation of the elevational head difference with the kinetic energy. The appropriate flow velocity was calculated using the entire face area of the grate. Three different data sets are combined on these graphs, corresponding to submergence depths of 0.25, 0.5 and 1 foot depths. Some transitions to other modes of operation are evident, especially at a submergence depth of 0.25 foot. Results for 0.5 and 1.0 foot submergence were very similar. To obtain a measure of the loss factor associated with the addition of a grate, the data sets for 0.5 and 1.0 feet were combined and a linear regression was performed to give the total loss for the open inlet, the slotted grate and the reticuline grate configurations. The differences in the slopes with and without grate were then obtained by subtraction to give the grating loss factor. The results of these experiments are summarized in Table 1. The value of the total loss coefficient obtained when no grate is in place represents losses for the entire flow path and not just the inlet. This value has no significance for design purposes since it depends on the specific facility configuration. Also, it should be noted that these

diagrams are not general performance maps like Figure 2, but rather specialized diagrams constructed to illustrate the phenomenon described above.

As a further examination of the role of the air core vortex in performance, three points representing orifice performance were added to Figures 15-17. These points were derived from the three submergence heads used as differential heads and using the discharge coefficient to compute the discharge and hence the kinetic energy. It can be seen that for the 0.25 foot submergence head the points lie very close to the transition away from full flow operation. Similar tendencies may be detected for the 0.5 foot submergence head, although the result is not definitive. It appears that for lower submergence, sufficient air is aspirated into the box immediately below the grate to force an orifice mode of operation.

A more limited experiment was conducted with the crossbar grating material. Here submergence head was held at 0.5 feet and the results compared to the results and correlation for the same tests performed with the reticuline grate. As in the orifice experiments, the purpose of the experiment was to eliminate the effect of the reticuline configuration. Very comparable performance was observed, as seen in Figure 18.

## CONCLUSIONS AND RECOMMENDATIONS

The hydraulic performance of the reticuline grate has been tested and compared to open inlets and other gratings under conditions of orifice and full flow. The performance of the grating is good, exceeding that of the slotted grate and comparable with crossbar grates of similar proportions. The results of this investigation are summarized in Table 1.

To properly compare the performance under orifice conditions, it is necessary to account for the difference in actual area. Comparing the product of the discharge coefficient and the area ratio (Equation 7) to the same product for an open inlet as a performance index (Table 1), indicates that the reticuline grate performs better than the slotted grate and approaches the open inlet.

Although it appears that the orifice discharge coefficient may be slightly enhanced by the addition of the grate, this effect will only partially offset the decrease in discharge as trash accumulates. The increase noted is probably due to a combination of vortex suppression and flow straightening that reduces separation effects. Since the discharge coefficient is only slightly reduced when an intensifier is applied, it is concluded that the values obtained may be used with reasonable confidence for design under sump conditions. Values for the discharge coefficient reported in Table 1 should be used with caution if substantial circulation exists in the pond or if significant approach velocity is present, since reduced performance may result.

The loss factors for full flow through the slotted grate and through the reticuline grate have been measured and may be utilized with the kinetic energy as calculated from the full face area of the grate. It is believed that these values will scale satisfactorily.

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More importantly, it is concluded that the reticuline grate has a substantially lower loss coefficient than the slotted grate. It is noted however that full flow may not be sustained over all operating conditions. Prediction of transition to other modes is difficult, if not impossible to predict or scale. Design based on minimum performance must therefore be recommended.

With regard to the observation of loss coefficient for full flow conditions, it was observed that air entrainment from the vortex can become a problem when a grate is added to the inlet. Buildup of air in the drain pipe eventually leads to air binding, accompanied by a large head loss. All the gratings tested seemed to cause this problem. It appears that the reason for this difference is that the grate promotes breakup of the air core of the vortex when the flow velocity is sufficient to carry small bubbles into the pipe. Since drain lines are not usually vented, it is important for the designer to anticipate the possibility that air binding may occur in the drain as a consequence of adding a grate, resulting in a substantially reduced capacity. Therefore, if a grating is present, the best performance under full flow conditions will be obtained with a vented drainline. Again, the prediction of the onset of air binding is design specific and not expected to scale.

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TABLE 1:  Summary of model parameters

| | NO GRATE | RETICULINE GRATE | SLOTTED GRATE | STRAIGHT BAR |
|---|---|---|---|---|
| a x b (ft) | .58 x.75 | .58 x .75 | .58 x .75 | .58 x .75 |
| SCALE | 1/4 | 1/4 | 1/4 | 1/4 |
| NOM. AREA (sq ft) | .44 | .44 | .44 | .44 |
| OPEN AREA FACTOR | 1 | .80 | .48 | .80 |
| GRATED AREA (sq ft) | .321 | .321 | .438 | .321 |
| ACTUAL AREA (sq ft) | .321 | .256 | .210 | .256 |
| AREA RATIO R | .733 | .584 | .479 | .584 |
| DISCHARGE ($C_D$) | .82 - .75 | .91 - .89 | .67 - .72 | .90 (est) |
| INDEX ($C_D$ X R) | .58 | .525 | .33 | .53 (est) |
| TOTAL LOSS FACTOR | 1.61 | 2.07 | 4.85 | — |
| GRATING LOSS FACTOR | — | .46 | 3.24 | .46 (est) |
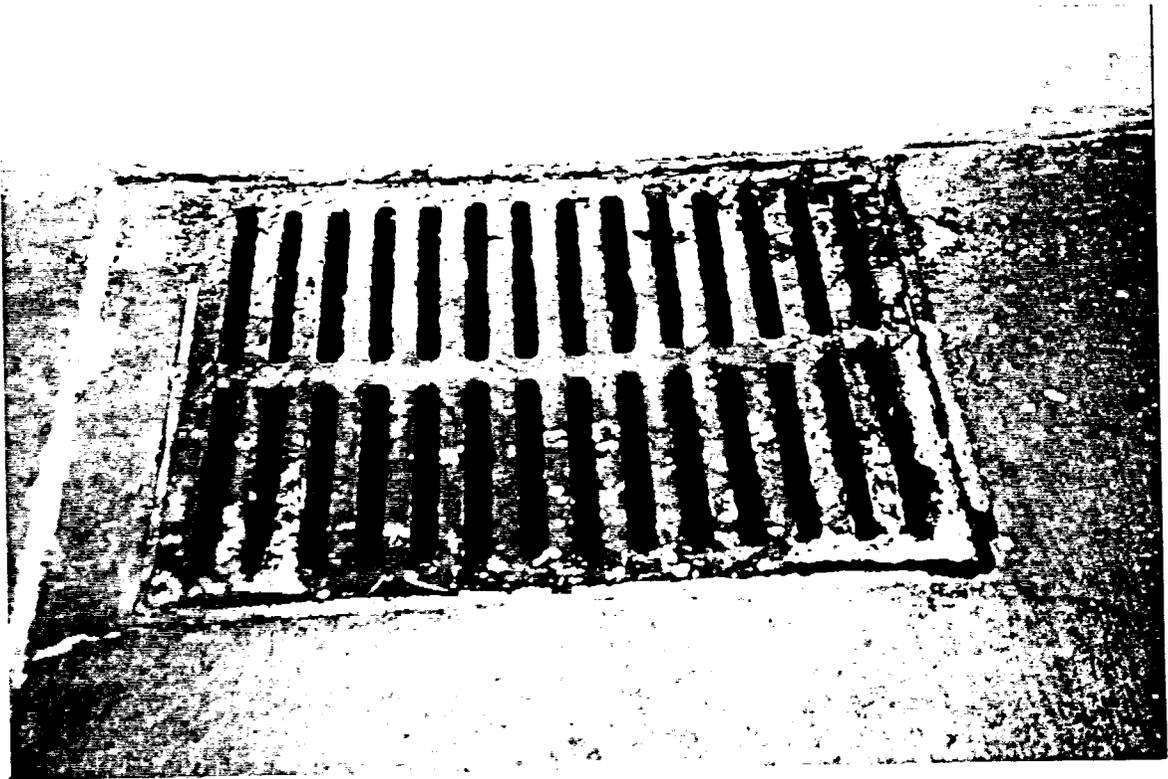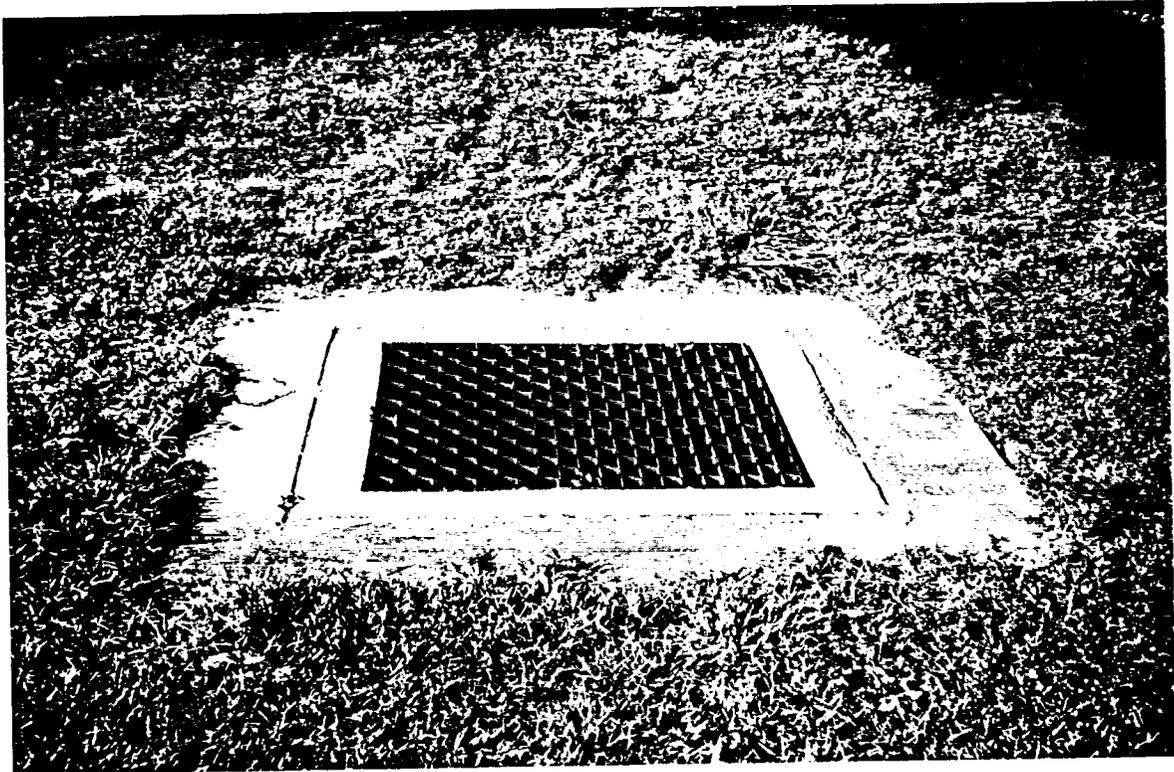
Figure 1: Examples of gratings examined. Above, reticuline grate installed in ditch bottom; below, slotted grate.

VORTEX

GRATE

FLOW

DRAIN BOX

SUBMERGENCE HEAD

FULL FLOW

VORTEX
ENVELOPE
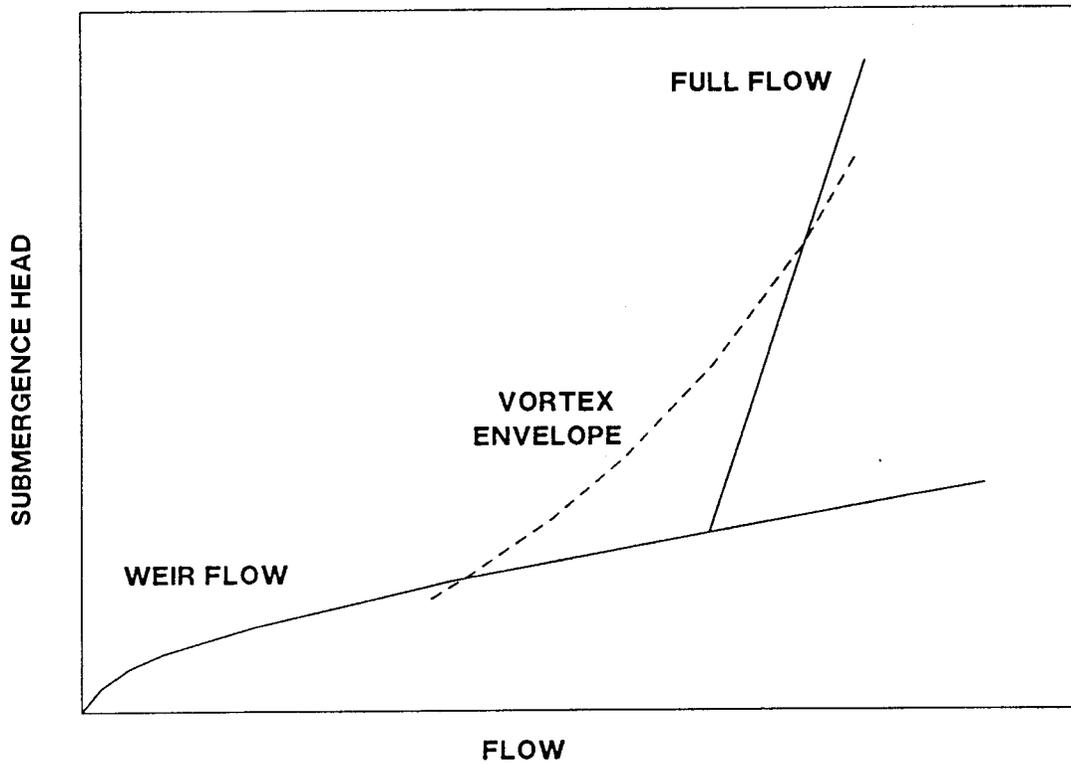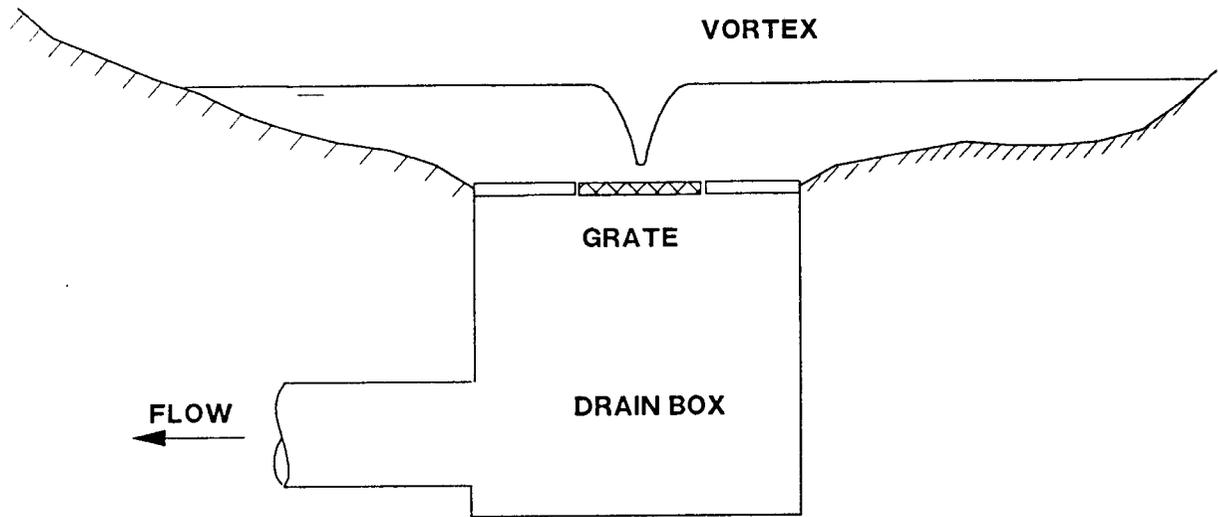
WEIR FLOW

FLOW

Figure 2: Illustrating the hydraulic performance of an inlet
structure. Performance map illustrates a situation with vortex
development between weir flow and full flow condition.
Other situations are possible.
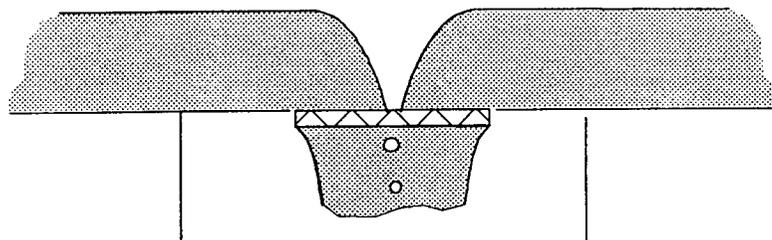
**A) ORIFICE FLOW**
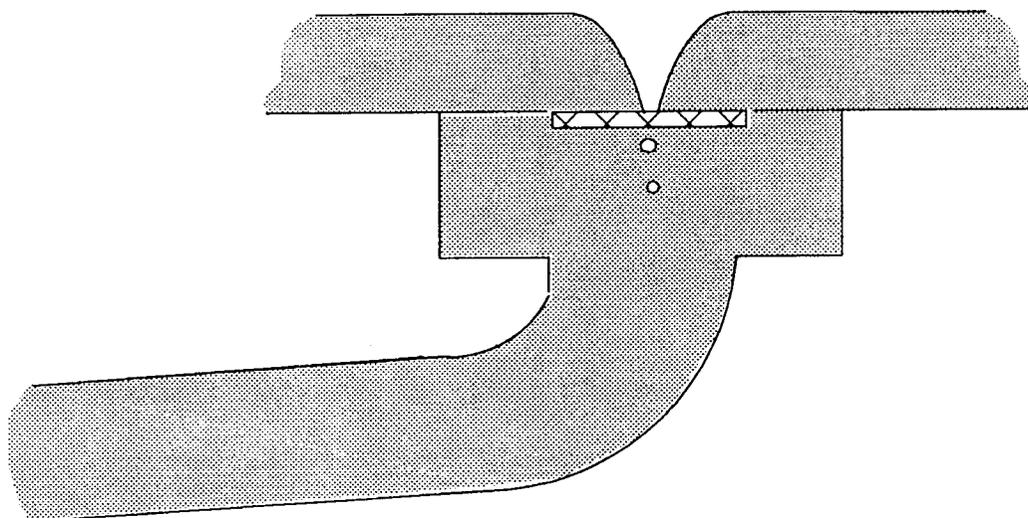


**B) FULL FLOW**

Figure 3: Comparison between orifice flow (shown above) and fully developed flow (shown below) through the inlet.

A) SURFACE DIMPLE

B) VORTEX PULLING
   FLOATING TRASH

C) CRITICAL STAGE
   FOR AIR ENTRAINMENT

D) AIR BUBBLE
   ENTRAINMENT
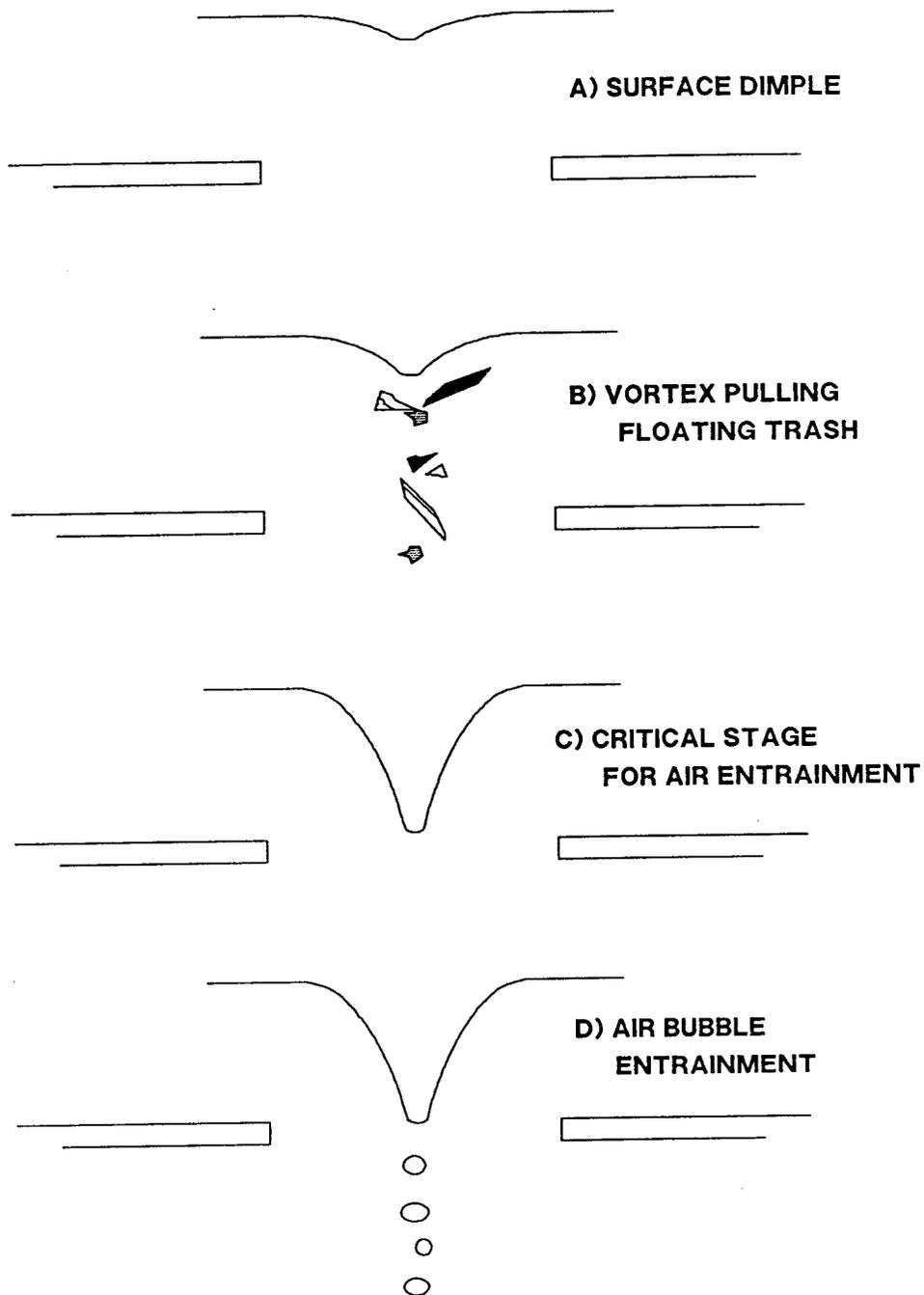
**Figure 4:** Vortex development above an inlet. As the vortex grows stronger, floating debris is sucked down, followed by a developing air core.
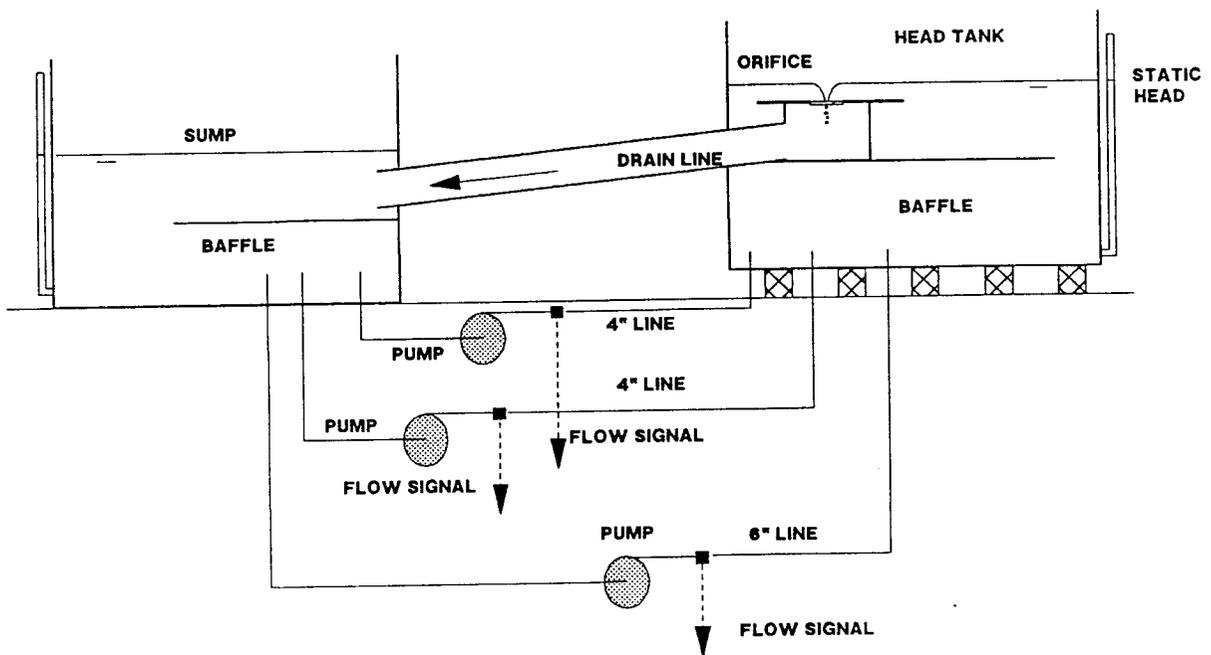
**Figure 5: Experimental facility.**

**VORTEX**

**A) UNMODIFIED INLET**

**B) VORTEX STIMULATOR**

**C) RADIAL VANE SUPPRESSOR**

**D) ANTI-VORTEX WALL**
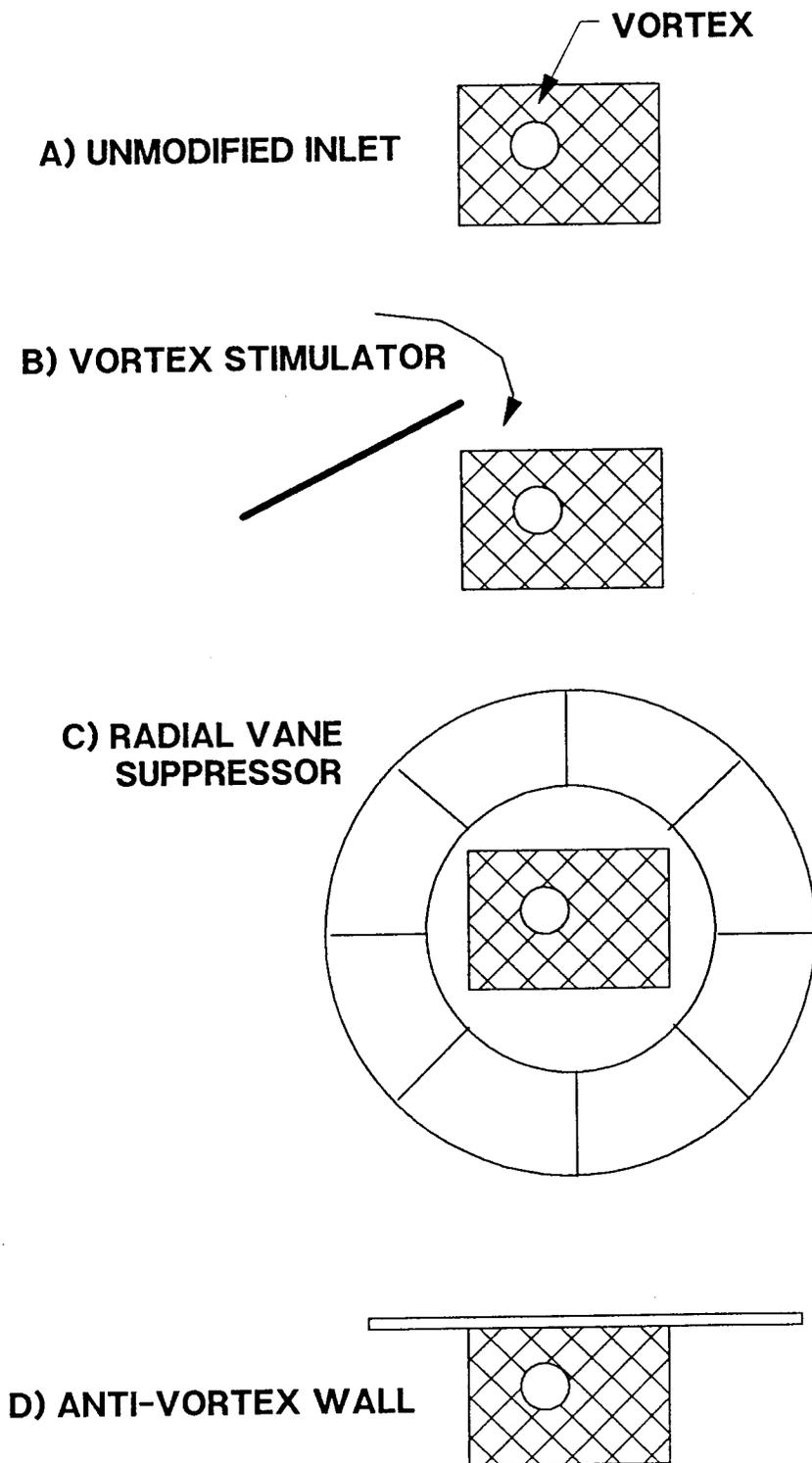
Figure 6: Various experimental modifications to inlet flow.
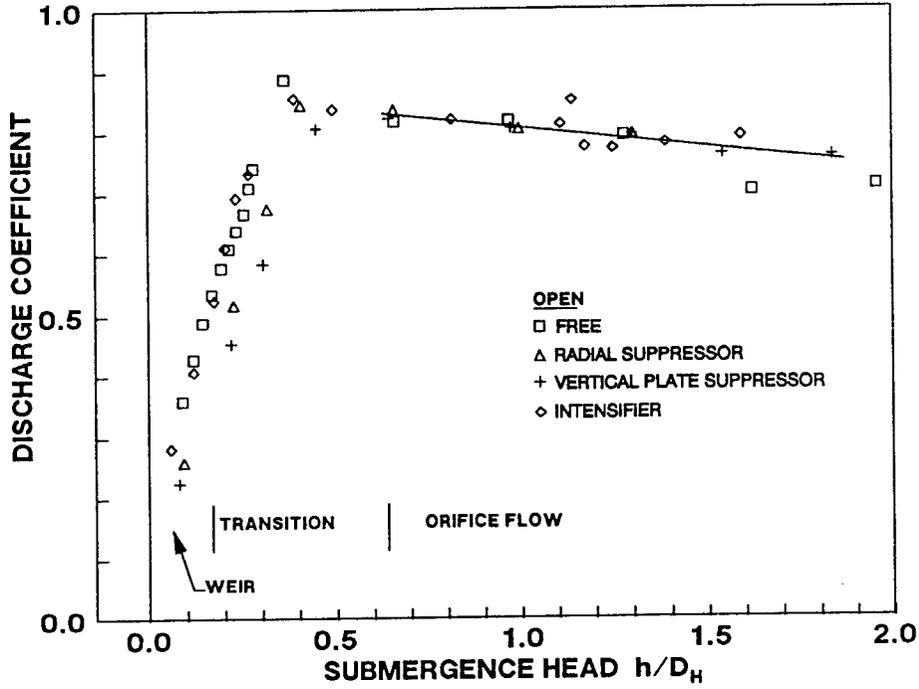
**Figure 7: Orifice discharge coefficient as a function of nondimensional head above the inlet with no grate in place. Solid line approximates discharge coefficient for all data sets except intensified circulation.**
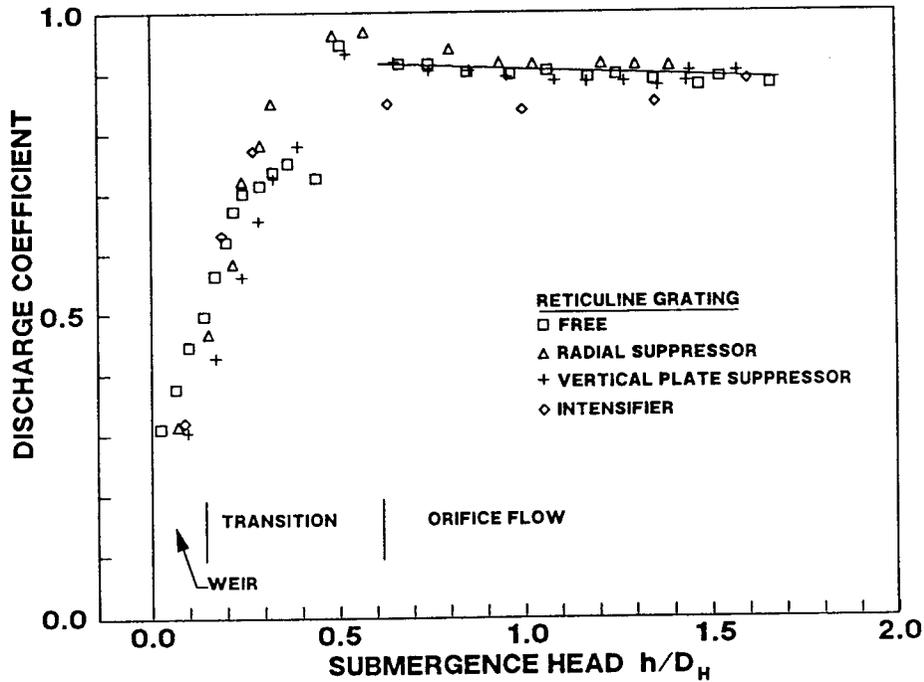


**Figure 8: Orifice discharge coefficient as a function of nondimensional head above the inlet with the reticuline grate in place. Solid line approximates discharge coefficient for all data sets except intensified circulation.**
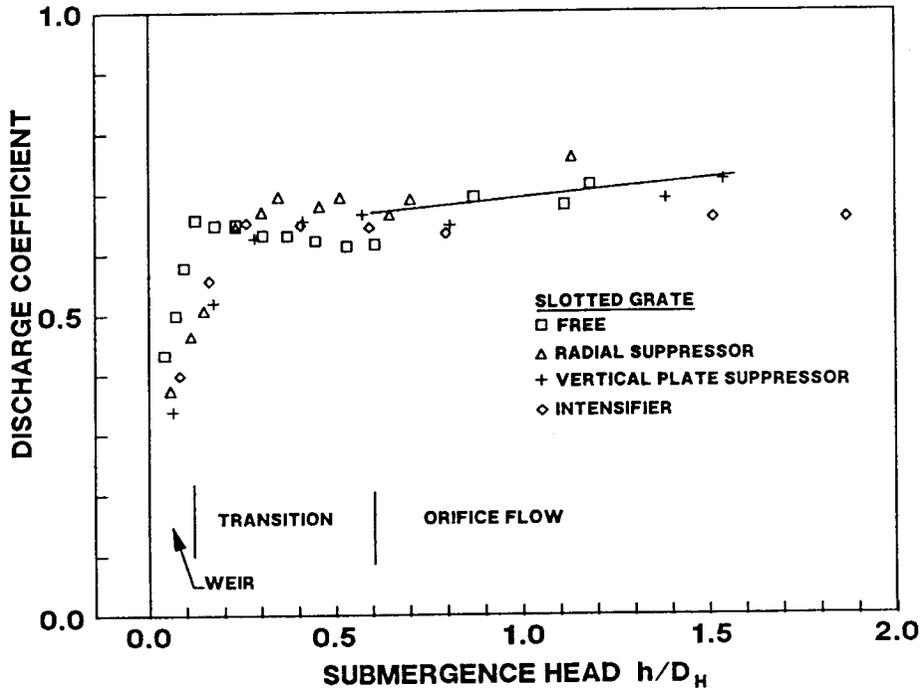
Figure 9: Orifice discharge coefficient as a function of nondimensional head above the inlet with the slotted grate in place. Solid line approximates discharge coefficient for all data sets except intensified circulation.
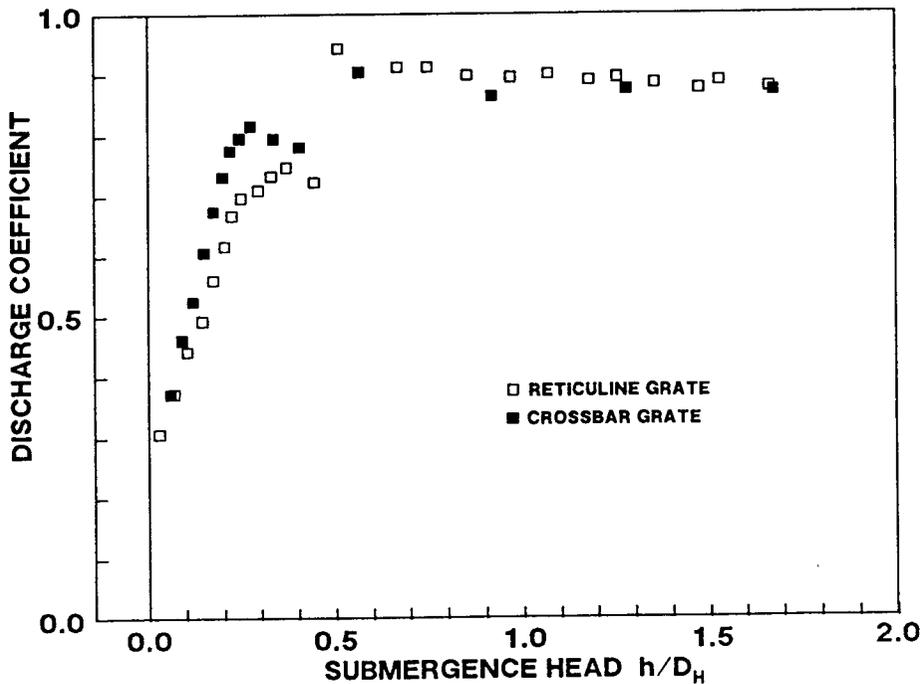


Figure 10: Comparison of orifice discharge coefficient for the reticuline grate and crossbar grating.
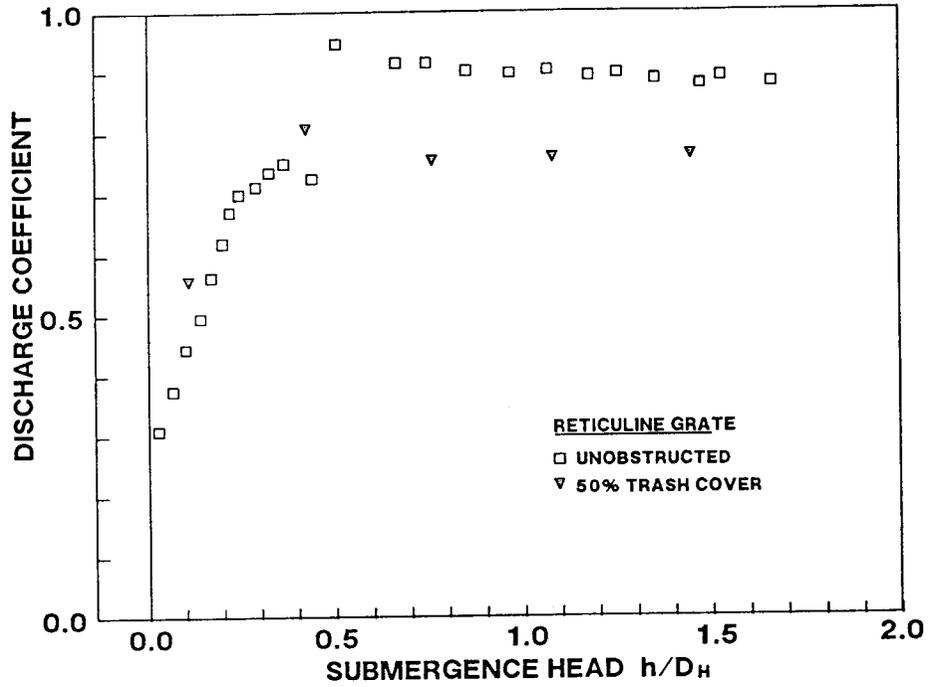
Figure 11: The effect of 50% trash cover on the reticuline grate.
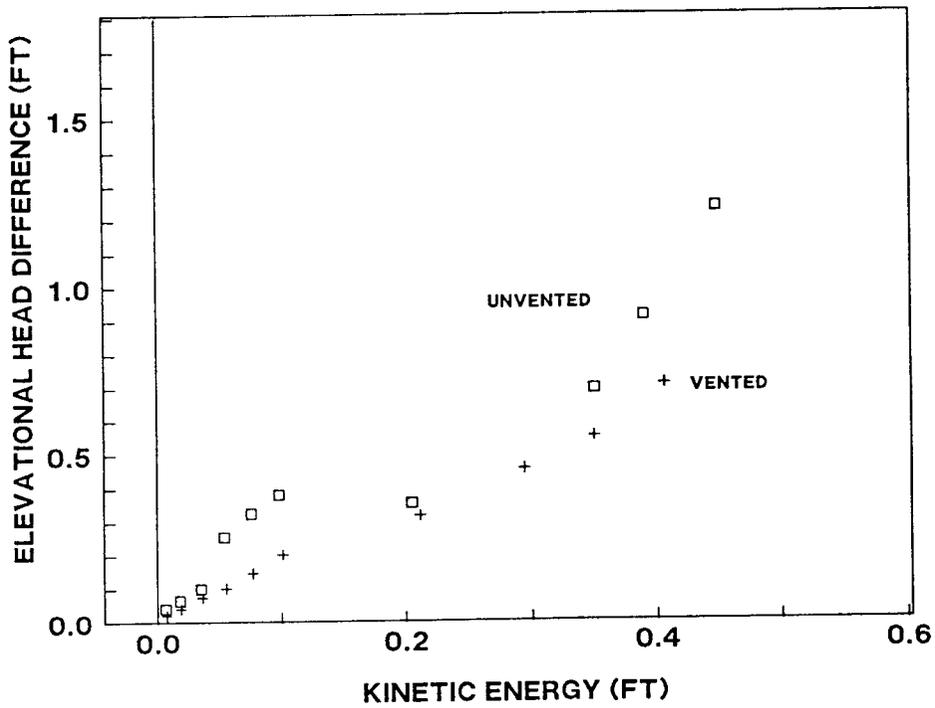


Figure 12: Comparison between vented and unvented drainlines during full flow experiments with no grate present (submergence head is 0.5 feet).
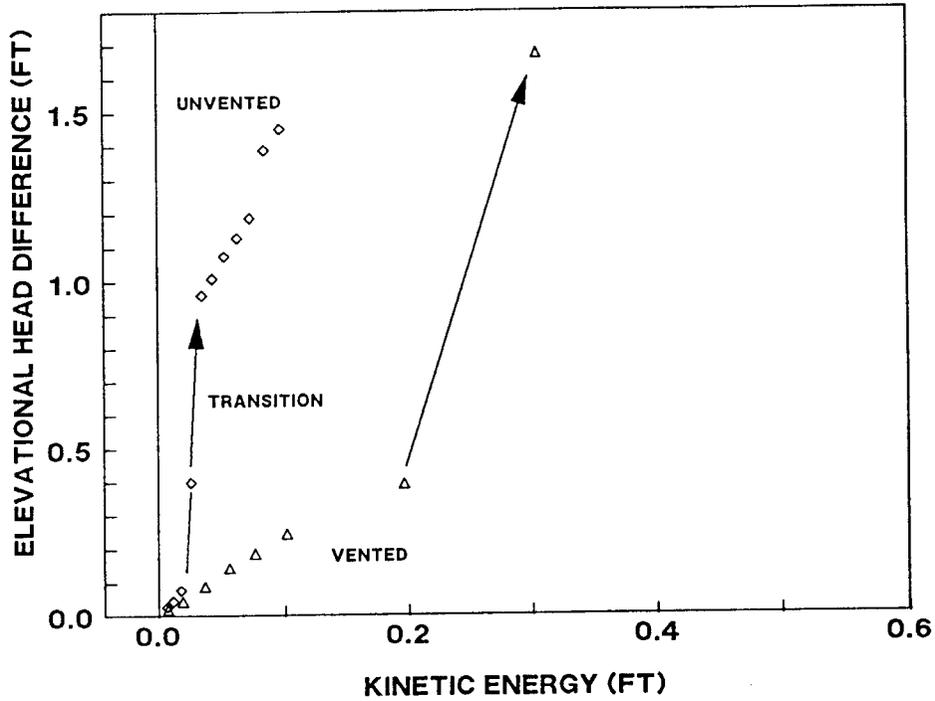
**Figure 13: Comparison between vented and unvented drainlines during full flow experiments with reticuline grate (submergence head is 0.5 feet). Note the early jump to a high head operating regime when the line is unvented.**
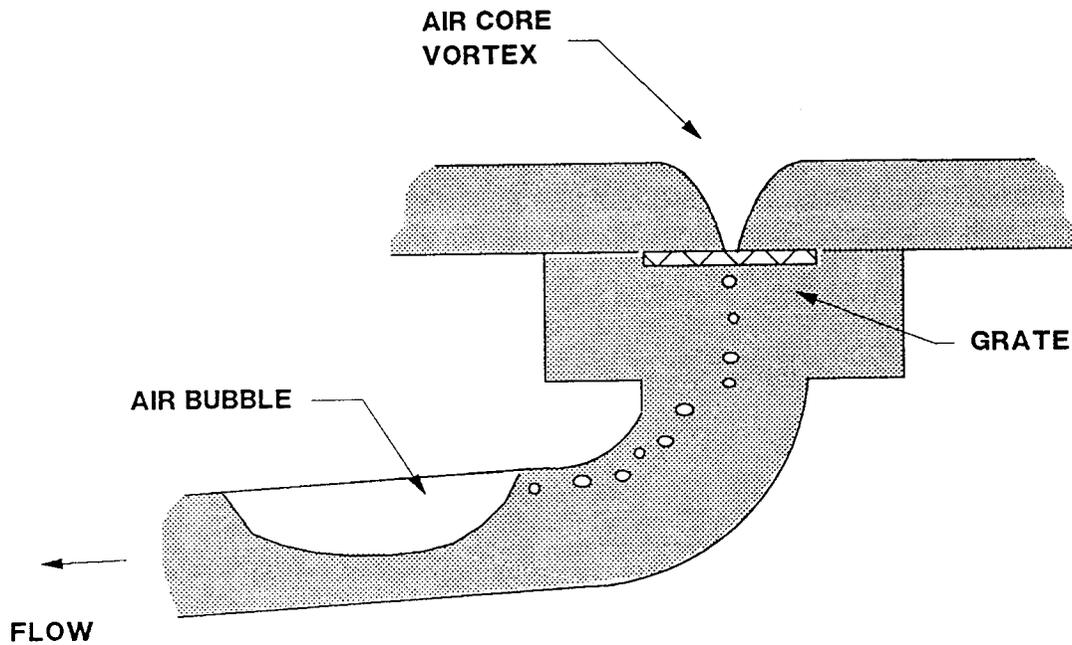


**Figure 14: Illustrating the mechanism resulting in air binding in drainline. Vortex penetrates the grating, breaking the air core into small bubbles that accumulate in the drainline.**
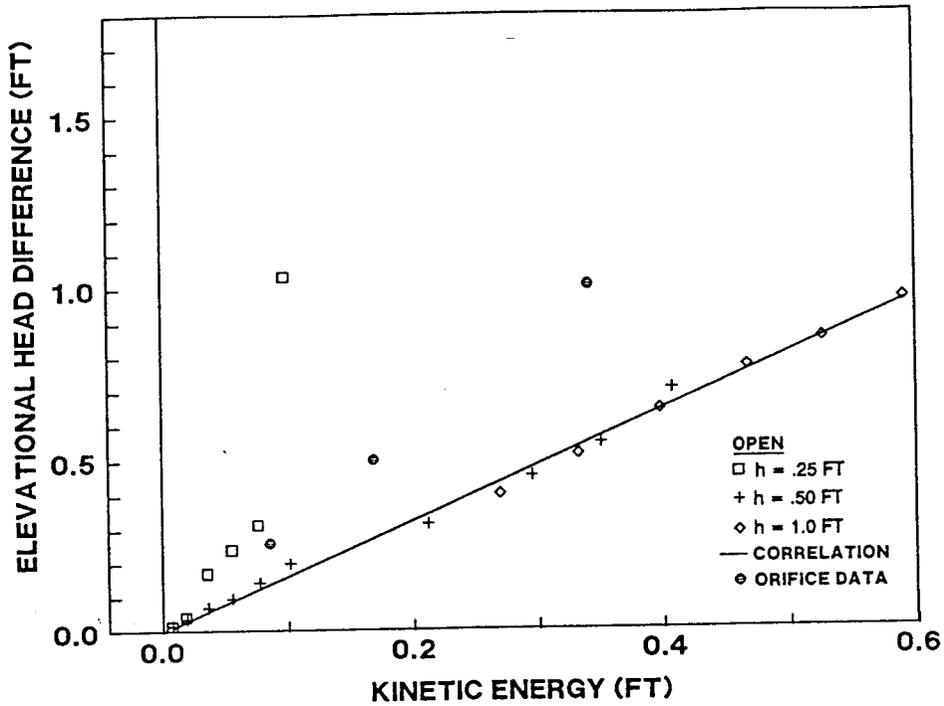
Figure 15: Correlation between elevational head difference and kinetic energy when no grate is in place. Solid line indicates regression for combined data sets at submergence heads of 0.5 and 1.0 feet.
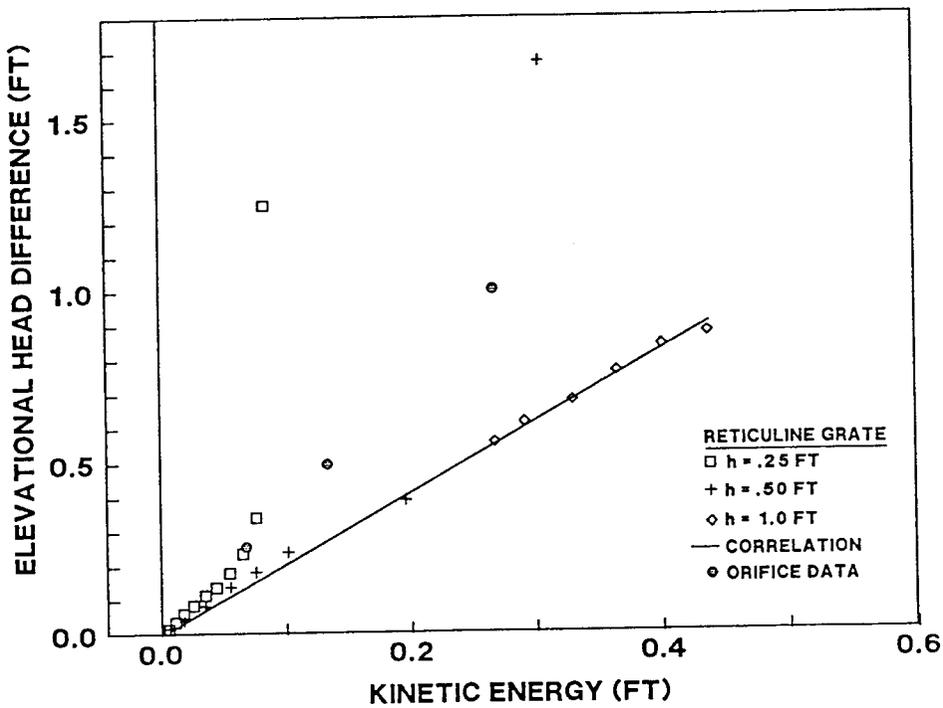


Figure 16: Correlation between elevational head difference and kinetic energy when the reticuline grate is in place. Solid line indicates regression for combined data sets at submergence heads of 0.5 and 1.0 feet.
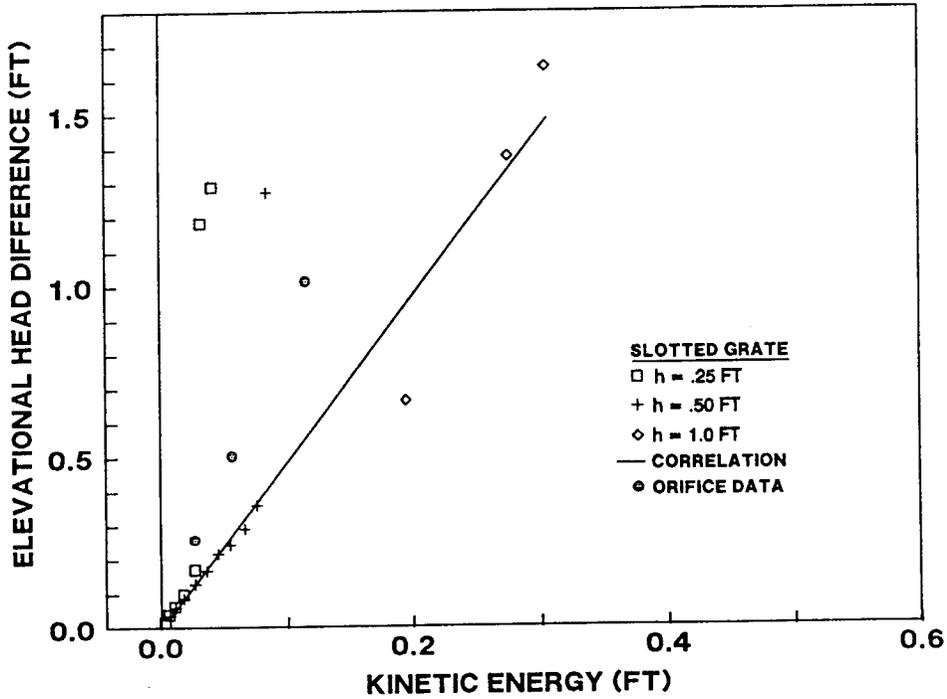
Figure 17: Correlation between elevational head difference and kinetic energy when the slotted grate is in place. Solid line indicates regression for combined data sets at submergence heads of 0.5 and 1.0 feet.
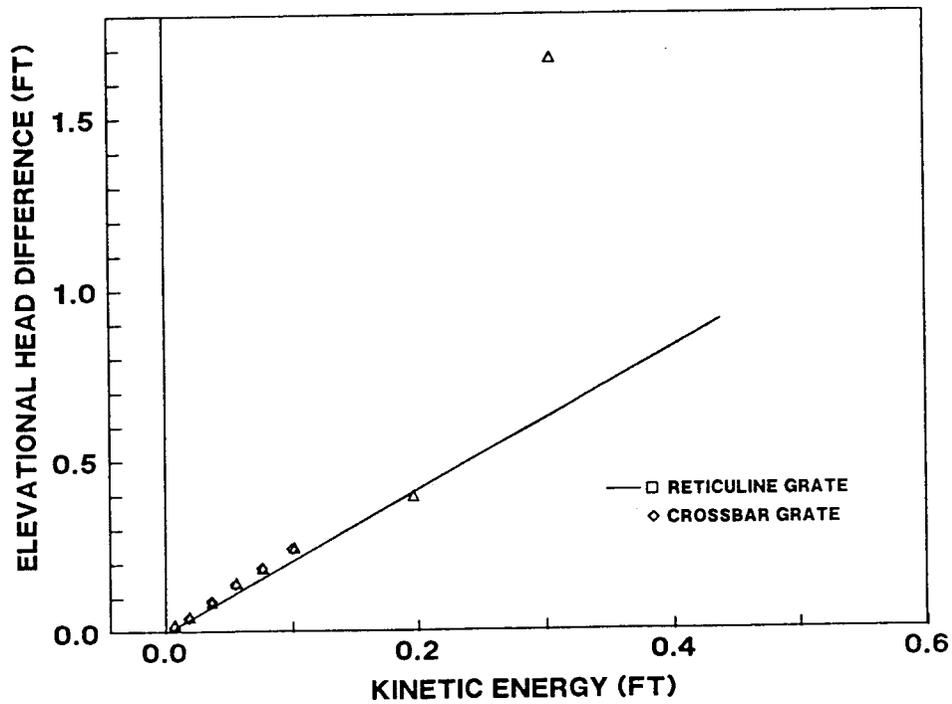


Figure 18: Comparison of full flow performance at 0.5 feet submergence between the reticuline grate and crossbar grating material.