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A STUDY OF FLOW CONDITIONS IN SHAFT SPILLWAYS

A THESIS

Presented to

The Faculty of the Graduate Division

by

Yusuf G. Mussalli

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

In the School of Civil Engineering

Georgia Institute of Technology

November, 1969

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A STUDY OF FLOW CONDITIONS

IN SHAFT SPILLWAYS

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NOMENCLATURE

Symbol	Quantity	Dimensions (F,L,T)
A	area of the water flow in the conduit	L^2
A_a	area of the air flow	L^2
A_c	area of the horizontal conduit	L^2
A_o	area at the throat of the vertical transition	L^2
A_s	area at the bottom of the vertical shaft	L^2
B	dimension of the square conduit	L
C	coefficient of discharge for weir flow	none
C_o	coefficient of discharge for orifice flow	none
C_s	coefficient of discharge for short-tube flow	none
d	depth of water flow in horizontal conduit	L
d_1	depth of the supercritical flow upstream of a hydraulic jump	L
d_2	depth of the subcritical flow downstream of a hydraulic jump	L
D	diameter of the shaft	L
D_b	diameter of the bend	L
D_c	diameter of the horizontal conduit	L
D_{cr}	diameter at the inlet crest	L
D_e	equivalent diameter	L

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Symbol	Quantity	Dimensions (F,L,T)
D_j	diameter of the falling water jet	L
D_{th}	diameter of the throat of the vertical transition	L
f	Darcy-Weisbach friction factor	none
F	Froude number	none
g	gravitational acceleration	LT^{-2}
h	difference of elevation between the pool surface and the spillway crest	L
h_f	head loss due to friction	L
h_L	head loss from all causes	L
h_v	velocity head	L
H	total head over spillway crest	L
H_c	difference in elevation between spillway crest and invert of horizontal conduit at the outlet	L
H_e	difference in elevation between pool surface and invert of culvert entrance	L
H_o	total head over throat section	L
H_s	total head referenced to bottom of vertical shaft	L
H_x	total head over a section x-x	L
K	total loss coefficient	none
K ent.	entrance loss coefficient	none
K_f	friction loss coefficient	none
K_v	velocity head coefficient	none
L	length of horizontal conduit	L
n	Manning roughness coefficient	$L^{-1/3}$ T

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Symbol	Quantity	Dimensions (F,L,T)
p_a	air pressure	FL^{-2}
P	wetted perimeter	L
P_f	power dissipated due to friction	LFT^{-1}
q_a	air discharge per unit length	L^2T^{-1}
Q	water discharge	L^3T^{-1}
Q_a	air discharge	L^3T^{-1}
r	mean radius of bend	L
R	hydraulic radius	L
R_e	Reynolds number	none
S	bottom slope of an open channel	none
t	thickness of deflector	L
V	velocity of water flow	LT^{-1}
V_a	velocity of air flow	LT^{-1}
X	height of air pocket under lower nappe of flow over sharp-crest weir	L
y	thickness of outflowing air layer	L
Y	distance of free fall in shaft to the level of the hydraulic grade line	L
z	approach depth at a weir	L
Z	distance from the crest to the vertical hydraulic jump in the shaft	L
γ	specific weight	FL^{-3}
μ	dynamic viscosity	FTL^{-2}
ν	kinematic viscosity	L^2T^{-1}

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Symbol	Quantity	Dimensions (F,L,T)
σ	surface tension	FL^{-1}

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SUMMARY

The objective of this investigation is to study the flow conditions in shaft spillways in order to develop design information.

An extensive review of literature of vertical-shaft spillways is presented. The horizontal conduit is designed to flow partly full at all discharges, since the transition from partly-full to full-pipe flow (sealing) is accompanied by vibrations of the structure and surging of the flow. The major effort of this investigation was to determine experimentally the flow conditions associated with incipient sealing in the horizontal leg of the spillway.

The experimental study was done in a 4 in.-by-4 in. square conduit with three different circular bends, with various deflectors, and with various concentrations of air admitted with the water falling down the vertical shaft.

Sealing depends on the Froude number of the flow in the horizontal conduit. To maintain partly-full flow, more space is needed above the water-flow area with an increase of Froude number. With short-tube control, the ratio of the radius of curvature along the centerline to the bend diameter, r/D_b, and the deflector thickness at the crown of the bend determine the water-flow area in the horizontal conduit. Ventilation of the conduit delays sealing while aeration of the water flow hastens sealing. With weir control, waves on the flow surface hastens sealing and highly aerated flow delay sealing. Ratios of radius of curvature along the centerline to the bend diameter, r/D_b, larger

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than 2.0 are recommended, since bends of larger ratios of r/D_b generate less waves.

A general discussion on shaft spillways is presented covering: vertical versus inclined shaft spillways, free versus submerged inlet, partly-full versus full conduit, conduit-size determination, bend curvature, and air demand. Design examples are also presented.

The results of this study are not aimed to eliminate the need of model studies but rather to enable the designer to make better initial designs.

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CHAPTER I

INTRODUCTION

The purpose of this study is to develop design concepts for shaft spillways. In this chapter the shaft spillway is described, the discharge characteristics are discussed, the known design information is reviewed, and the need for additional design information is pointed out.

A. Description of a Shaft Spillway

1. General

Spillways are provided to release surplus or flood water which can not be contained in the allotted storage space at storage and detention dams. There are various types of spillways such as: overfall, channel, and tunnel spillways.

A shaft spillway is a tunnel spillway in which the excess flood water enters over a horizontally positioned inlet, drops through a vertical or inclined shaft, and then flows to the downstream river channel through a horizontal or nearly horizontal conduit. Typical vertical and inclined shaft spillways are shown in Figures 1a and 1b.

2. Elements of a Vertical Shaft Spillway

A vertical-shaft spillway consists of the following elements: a weir inlet structure, a vertical transition, a vertical shaft, a vertical bend, a horizontal conduit, and an outlet structure as shown in Figure 2. Auxiliary elements may also be added.

The inlet structure is usually a circular weir. There are two

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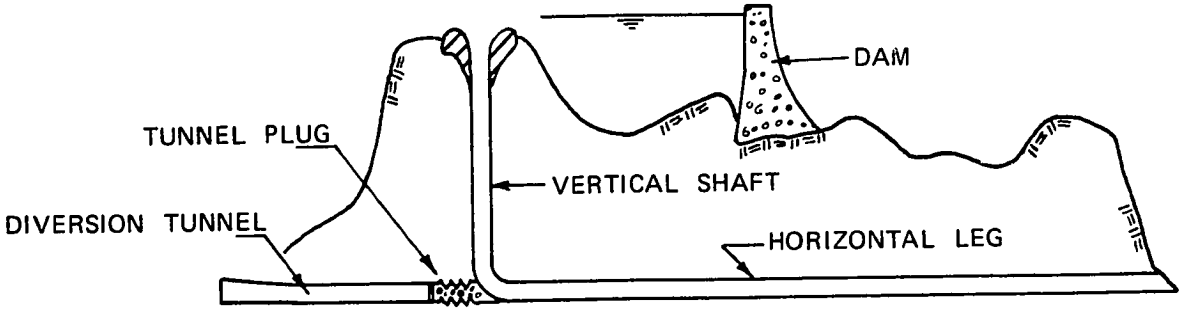
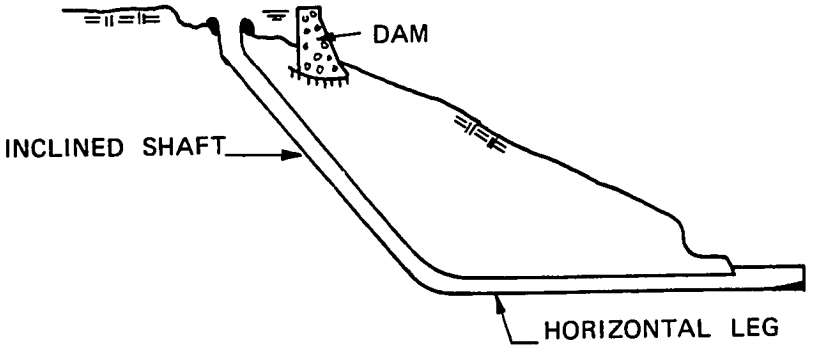


(a) VERTICAL SHAFT SPILLWAY



(b) INCLINED SHAFT SPILLWAY

Figure 1. Typical Shaft Spillways

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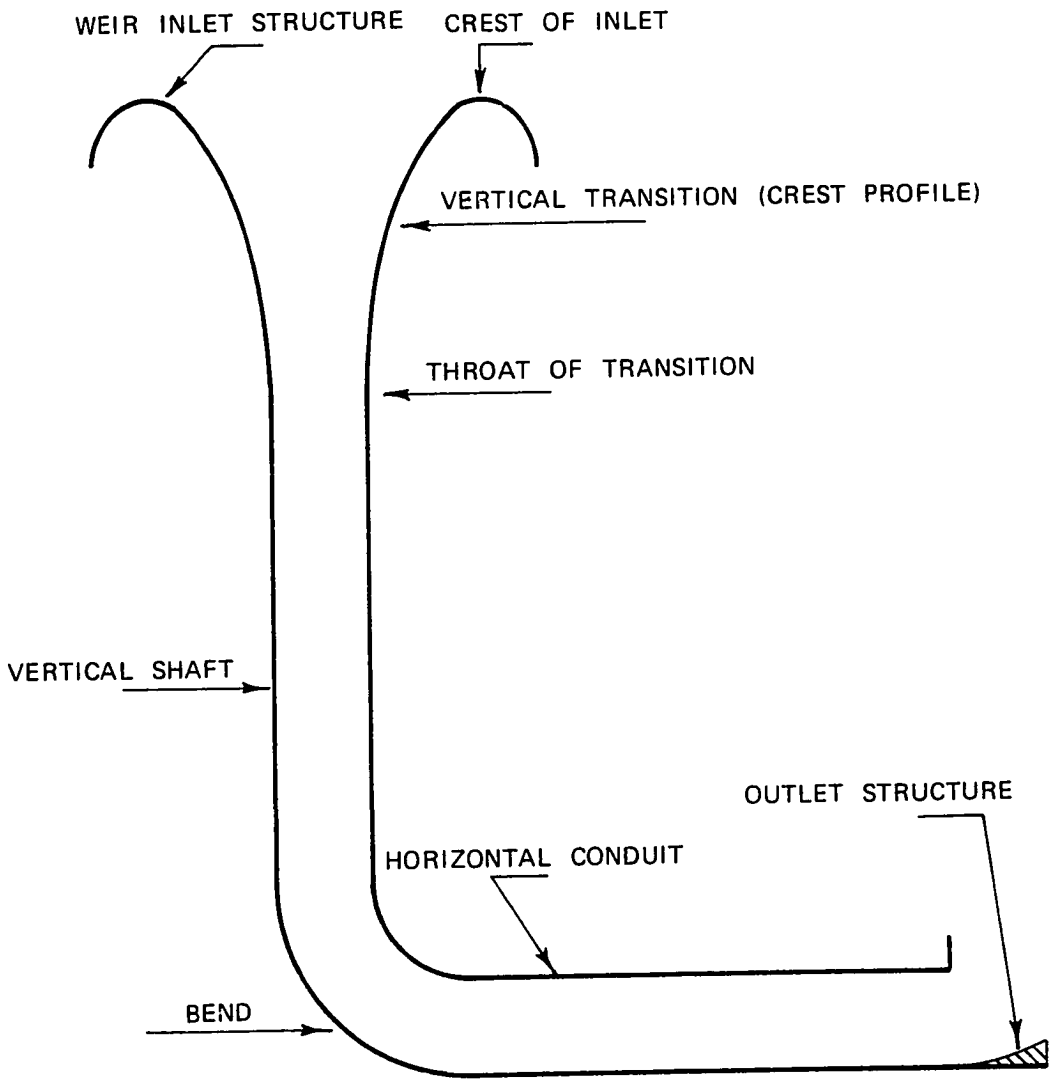

Figure 2. Elements of a Vertical Shaft Spillway

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types of inlet crests, the standard crest and the flat crest as shown in Figures 3a and 3b.

The vertical transition between the inlet crest and the vertical shaft is formed in the shape of an aerated lower nappe of a flow over a sharp-crested circular weir. The junction between the transition and the vertical shaft is the throat of the transition. This type of spillway inlet structure is often called a "morning glory", "glory hole", or "bellmouth" spillway.

The vertical shaft cross section is designed to accommodate the design flow and is made with a constant diameter for ease of construction.

The vertical bend connects the vertical shaft to the horizontal leg of the spillway. The bend is usually a simple circular bend. The curvature of the bend is chosen so as to facilitate the passage of timber logs and bulky debris which inadvertently might enter the spillway.

The horizontal leg of the spillway is usually a part of the diversion tunnel which diverts the river water while constructing the dam. The horizontal conduit is designed to flow either full or partly full throughout the discharge range because the transition from open-channel flow to pipe flow is accompanied by surging of the flow which results in undesirable vibrations.

The outlet structure is usually either a flip bucket or a sloping apron with a conventional stilling basin. The flip-bucket outlet directs the high velocity water into the air where much of the excess energy is dissipated prior to falling back into the river. In a conventional stilling basin, the excess energy is dissipated by turbulence generated in a hydraulic jump.

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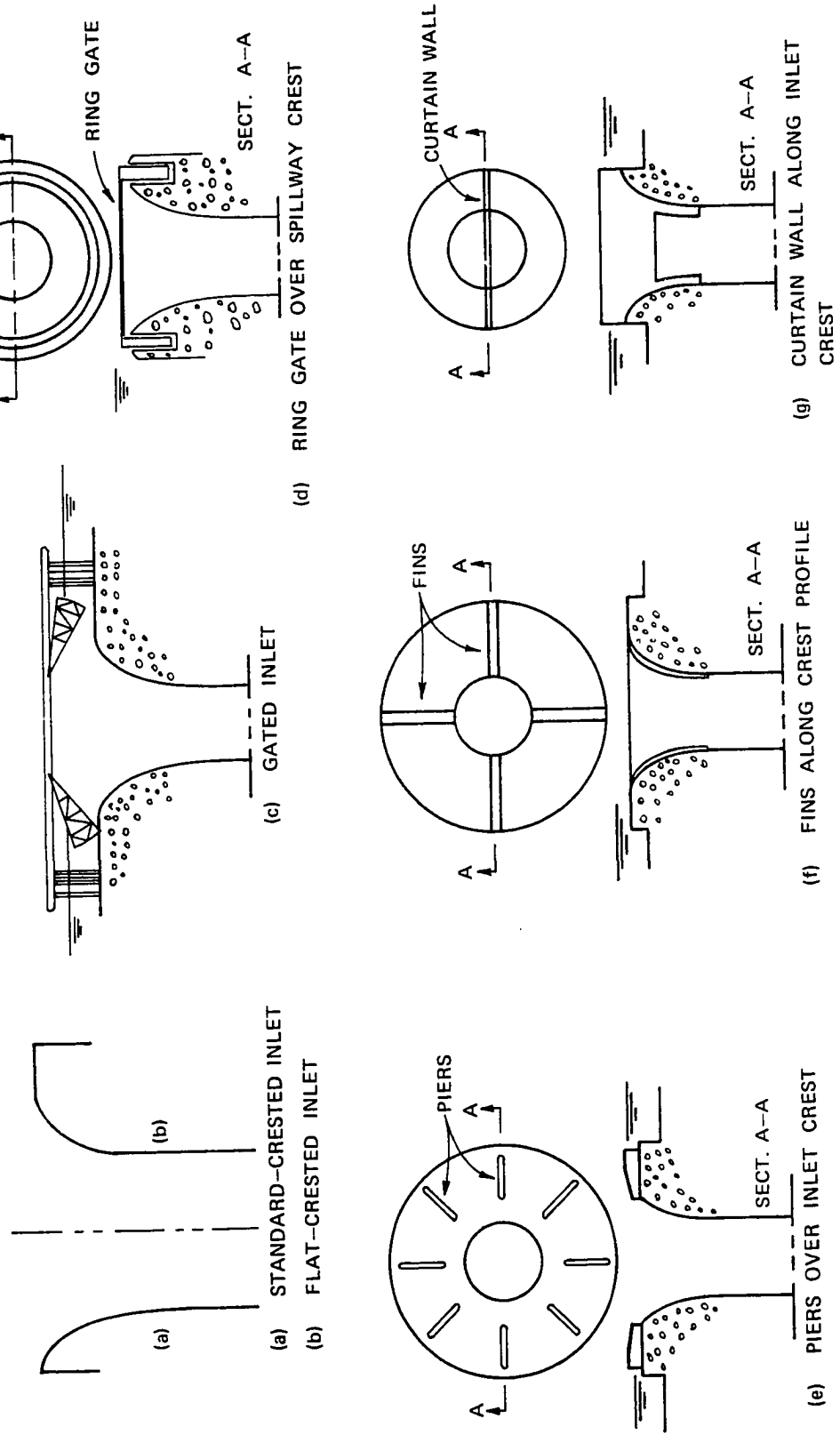

Figure 3. Structural Elements of the Inlet Crest

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Auxiliary structural elements are added to a shaft spillway to improve the flow conditions if needed. The inlet can be gated as shown in Figures 3c and 3d to control the pool elevation. Anti-vortex arrangements such as piers over the inlet crest (Figure 3e), fins along the crest profile (Figure 3f), or a curtain wall across the inlet (Figure 3g) are added to break vortex action which decreases the discharge capacity and which can cause increased wave action further down the conduit. A deflector can be added at the inner wall of the throat (Figure 4b), at the crown of the bend (Figure 4d), or at the roof of the upstream end of the horizontal conduit (Figure 4e) to suppress wave action further along the axis of the conduit. Air vents can be added at the throat of the shaft (Figure 4b), along the inclined or vertical shaft (Figure 4c), below the deflector at the crown of the bend (Figure 4d), after the deflector at the upstream end of the horizontal conduit (Figure 4e), or along the roof of the horizontal conduit (Figure 4f) to relieve negative pressures and to aerate the flow.

3. Discharge Characteristics of a Shaft Spillway

Typical flow conditions and discharge characteristics of a shaft spillway are shown on Figure 5.

For small heads over the inlet weir crest the discharge is weir flow with,

$$Q \propto |H|^{1.5}$$

in which Q is the discharge and H is the total head over the spillway crest. The vertical transition beyond the crest flows partly full. The flow clings to the sides of the shaft as shown in Figure 5a. Air is

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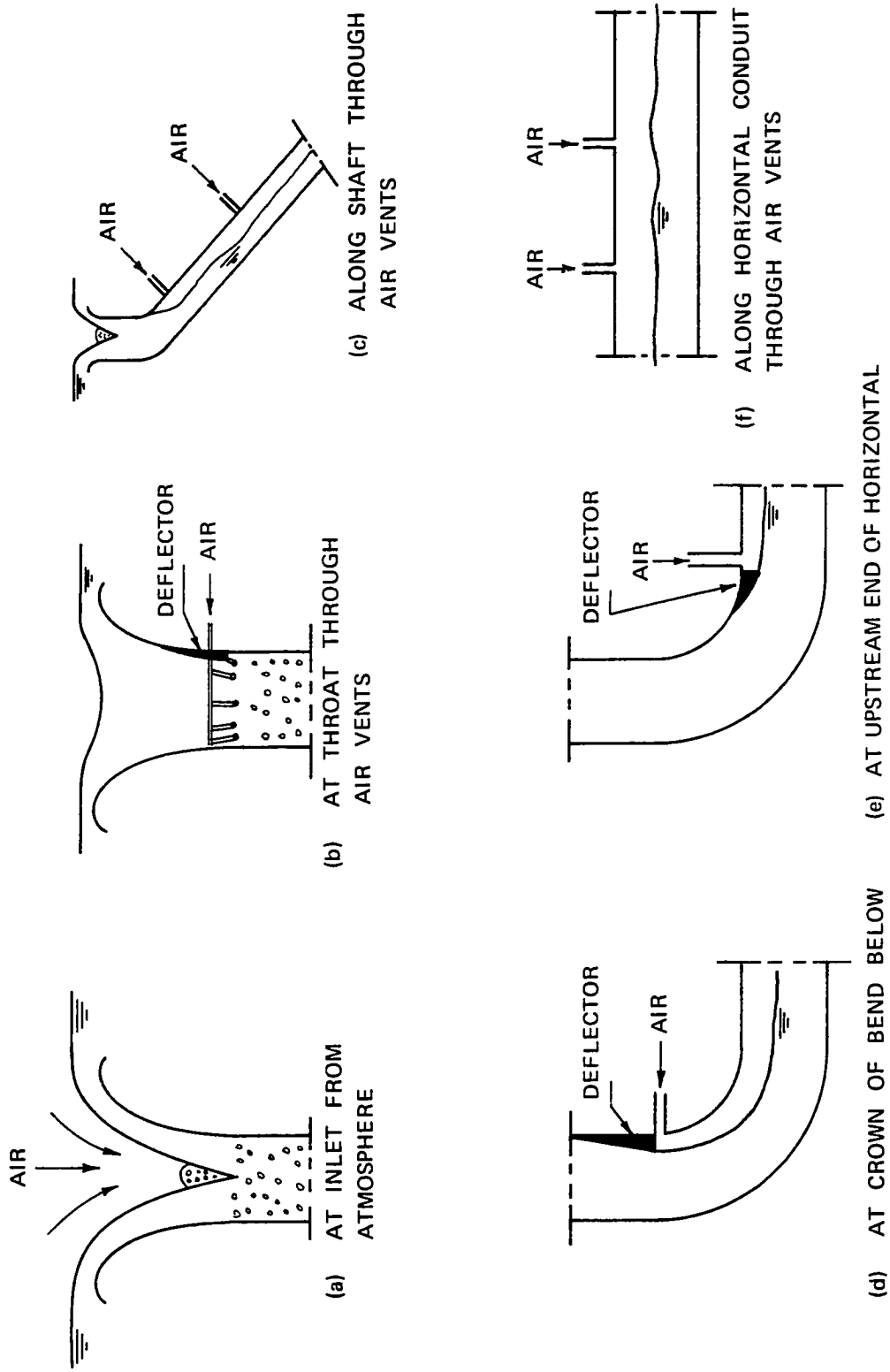

Figure 4. Aeration of a Shaft Spillway

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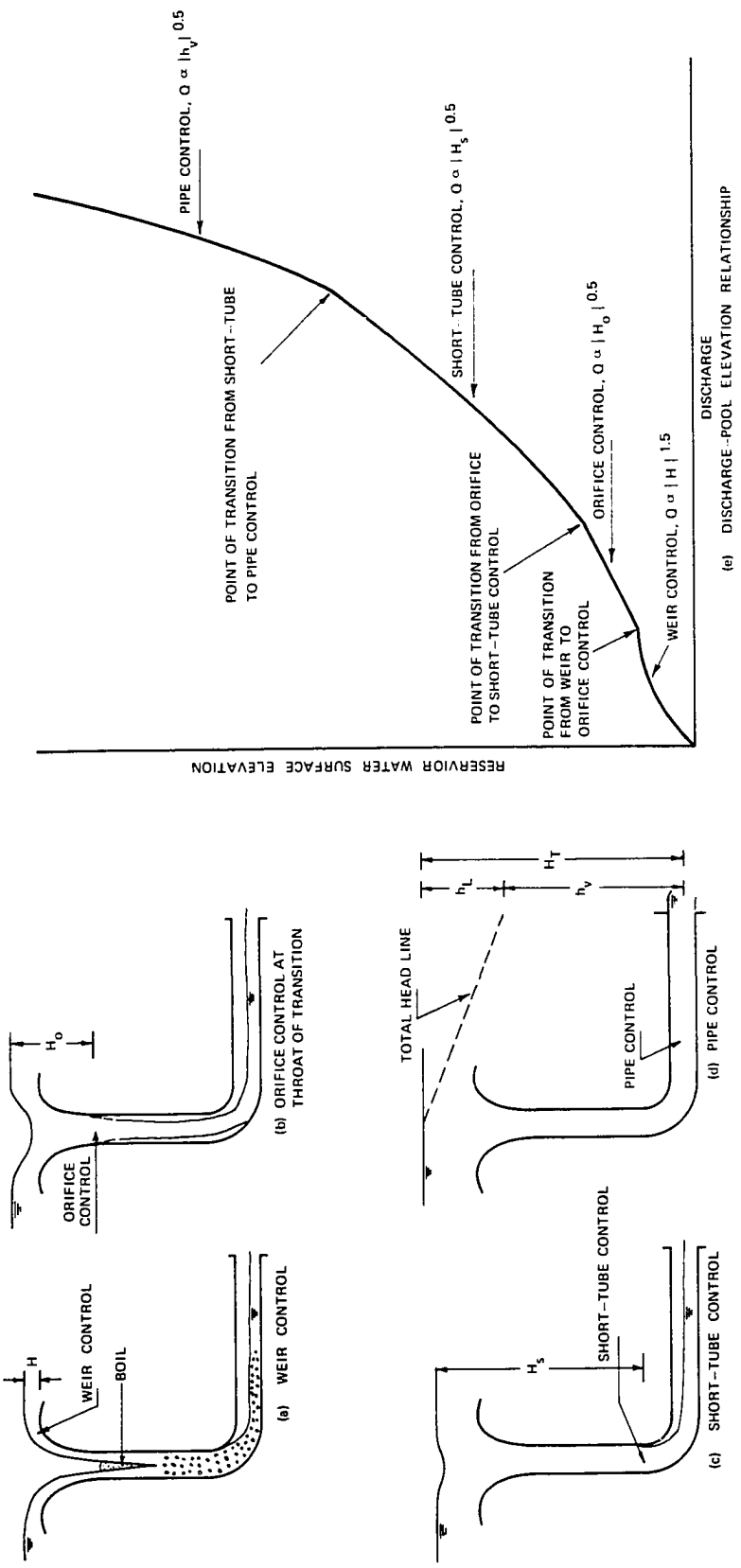

Figure 5. Nature of Flow and Discharge Characteristics of a Typical Shaft Spillway

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entrained into the flow from the atmosphere by the falling water as shown in Figure 4a. As the discharge over the crest increases, the overflowing annular nappe becomes thicker, and eventually the nappe flow converges into a vertical jet filling the vertical shaft. Subsequently, a water boil will occur in the vertical transition. The top of the boil becomes progressively higher with larger discharges until ultimately the flow submerges the crest.

After submergence of the crest occurs, the vertical transition flows full of water and the vertical shaft flows partly full as shown in Figure 5b. With this flow condition the inlet acts as an orifice for which

$$Q \propto |H_o|^{0.5}$$

in which H_o is the total head over the throat of the vertical transition. Air entrainment into the flow from the reservoir pool is negligible.

As the discharge increases, the vertical shaft flows full and the control shifts to the bottom of the shaft as shown in Figure 5c. The discharge is governed by the characteristics of short-tube flow at the bottom of the shaft with

$$Q \propto |H_s|^{0.5}$$

in which H_s is the total head over the bottom of the vertical shaft.

With further increase of discharge, the flow control shifts along the inner wall of the bend until the horizontal conduit flows full as shown in Figure 5d. The discharge is governed by the characteristics of

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pipe flow with

$$Q \propto |h_v|^{0.5}$$

in which h_v is the velocity head, $V^2/2g$, at the outlet portal as shown in Figure 5d.

The composite relationship between pool elevation and discharge is shown on Figure 5e.

The stage-discharge relationship for a particular shaft spillway varies with the proportional sizes of the inlet, vertical shaft, and the horizontal conduit as shown in Figure 6.

The ordinate of the point of transition from weir to orifice control is a function of the crest diameter, throat geometry, and shaft diameter. With a large ratio of crest diameter to shaft diameter, outflows are discharged over the weir at low heads, the vertical transition fills up, and orifice control occurs with a low head, H, on the crest as shown in Figure 6a. A deflector at the throat of the shaft as in Figure 4b, restricts the throat (Figure 2) resulting in a shift to orifice control at a lower pool elevation than without the deflector. Making the diameter of the vertical shaft larger than the diameter of the falling water jet as shown in Figure 6b, tends to maintain orifice control throughout a wider range of pool elevations than if the shaft diameter was smaller.

Similarly, the ordinate of the point of transition from weir to short-tube control is a function of the shaft diameter. Making the diameter at the bottom of the vertical shaft equal to or smaller than the

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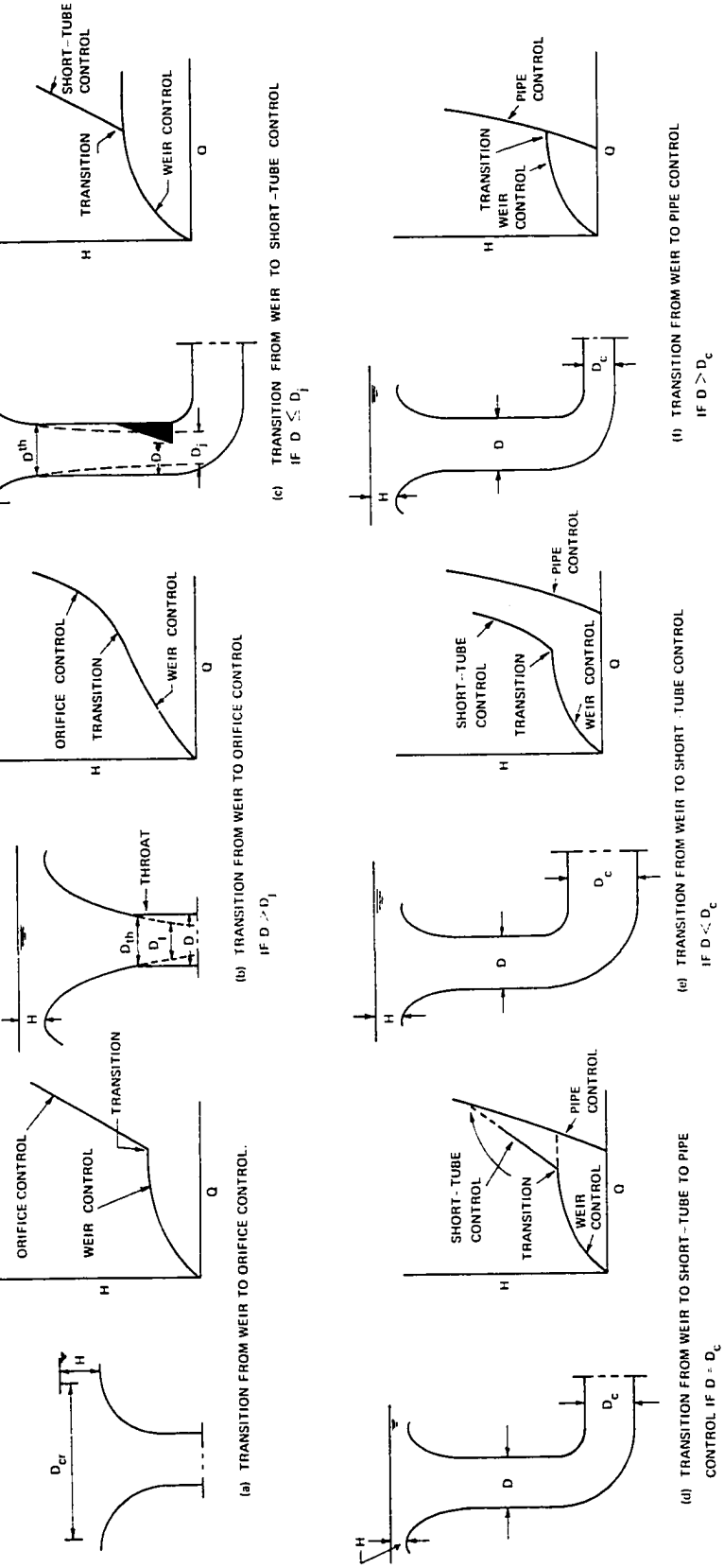

Figure 6. Effect of Geometric Proportioning on the Discharge Characteristics of a Shaft Spillway

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diameter of the falling water jet at that section such as by inserting a deflector as shown in Figure 6c, tends to fill the shaft with water before the flow is controlled at the throat, with the result that the flow control shifts directly from weir to short-tube.

Proportioning of the size of the horizontal conduit to the size of the vertical shaft changes the ordinates of the points of transition of the flow controls. If the size of the horizontal conduit is equal to that of the vertical shaft as shown in Figure 6d, the transition from weir to pipe control or from short-tube to pipe control occurs when the flow fills the horizontal conduit thus shifting the control to the outlet portal of the conduit. If the size of the horizontal conduit is greater than the size of the vertical shaft as in Figure 6e, the transition from weir to pipe control or from short-tube to pipe control might not occur, that is, the horizontal conduit flows partly full. If the size of the horizontal conduit is smaller than the size of the vertical shaft as shown in Figure 6f, the flow fills the horizontal conduit while the vertical shaft is flowing partly full with the result that the control shifts from weir to pipe.

The type of flow control desired depends on the purpose of the spillway. If the purpose is to pass excess flood water without overtopping the dam, the spillway will be designed to discharge freely with weir control throughout the discharge range. If the purpose is flood control where the discharge is to be limited in the river downstream from the dam, the spillway crest will be designed to operate unsubmerged with lower discharges and to operate submerged with higher discharges.

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4. Why a Shaft Spillway?

Shaft spillways provide a practical solution for spillways at earth and rockfill dams and at dam sites in narrow canyons where the abutments rise steeply.

A masonry or concrete dam combined with a spillway is no longer the standard solution for impounding water in a reservoir. Earth and rockfill dams are being used more frequently for this purpose. For reasons of safety and also of economy of construction, a spillway located away from the dam often provides the best solution.

At narrow dam sites, in a conventional concrete dam, the space is too limited to accommodate a straight overflow spillway. The necessary length of crest can be obtained with the circular weir inlet of the shaft spillway. In thin arch dams spillway openings over or through the dam present vibration problems. Difficulties are also experienced in hanging gates and control gear on such slender structures. Thus, the alternative of a spillway located away from the dam is a practical solution.

In all these situations the excess flood water can be carried around the dam by means of a shaft spillway. In case a diversion tunnel was already excavated to conduct the river around the site during construction, this diversion tunnel can also be used as the horizontal leg of the spillway as shown in Figure 1a. Thus, only the vertical shaft is needed to be excavated. With improved tunneling techniques the driving of shafts and tunnels can be carried out both rapidly and economically.

Hydraulically, the shaft spillway can be operated to fulfill the purpose of the dam. If the purpose is passing excess water, then

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the shaft spillway is designed to discharge freely with weir control with the result that near maximum capacity is attained at relatively low heads. If the purpose is flood control, then the shaft spillway is designed to discharge submerged.

B. Description of the Problem

The fact that shaft spillways are a small percentage of spillways for large dams is due, apart from considerations of suitability of site, to undesirable characteristics of shaft spillways as compared to unroofed spillways. The undesirable characteristics are: (1) submergence of the inlet, (2) increased possibilities for vibration, and (3) clogging of the spillway.

1. Submergence

The inlet of a shaft spillway submerges at a definite value of the ratio of the head over the crest to the diameter of the crest, H/D_{cr}. After submergence, little increase in discharge is gained with the rise of head over the crest as shown in Figure 5e. Submergence limits the effectiveness of the shaft spillway should the design discharge be exceeded, which would endanger the dam, especially an earth dam. To overcome this shortcoming, an emergency or auxiliary spillway can be incorporated to operate when the spillway design discharge is exceeded. Otherwise, the shaft spillway must be designed to operate unsubmerged with discharges resulting from the maximum probable flood.

2. Increased Possibilities for Vibration

Vibrations in a shaft spillway may be initiated (a) by a shift of the flow control and (b) by blow back of entrapped air pockets.

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a. Shift of Flow Control. Unstable flow conditions occur when the flow control shifts resulting in vibration of the structure. In a shaft spillway a shift of control can occur from weir to orifice control, from weir to short-tube control, from orifice to short-tube control, from short-tube to pipe control, and from weir to pipe control as shown in Figure 7.

(1) Weir to Orifice and Weir to Short-tube Control. If the profile of the transition between the crest and the vertical shaft is steeper than the profile of a lower nappe of an aerated flow over a sharp-crested circular weir, negative pressure develops in the air pockets underneath the lower nappe of the flow. Pressure fluctuations occur as intermittent amounts of air flow from the outlet to the air pockets. Pressure fluctuations can cause vibrations of the structure. As the water discharge increases, the water fills the shaft decreasing the possibility of air flow to the entrapped air pockets. The negative pressure in the air pockets sucks more water discharge and the shaft fills completely with water removing all the entrapped air. The flow control shifts from weir to orifice or from weir to short-tube with the reservoir surface elevation remaining the same as shown in Figure 7a. The sudden increase of discharge causes an abrupt increase in the dynamic load on the structure. Pressure fluctuations and the sudden shift of control can be eliminated by shaping the transition profile like that of a lower nappe of an aerated flow over a circular sharp-crested weir or by maintaining atmospheric pressure through ventilation.

(2) Orifice to Short-tube Control. If the diameter of the vertical shaft is larger than the diameter of the falling water jet

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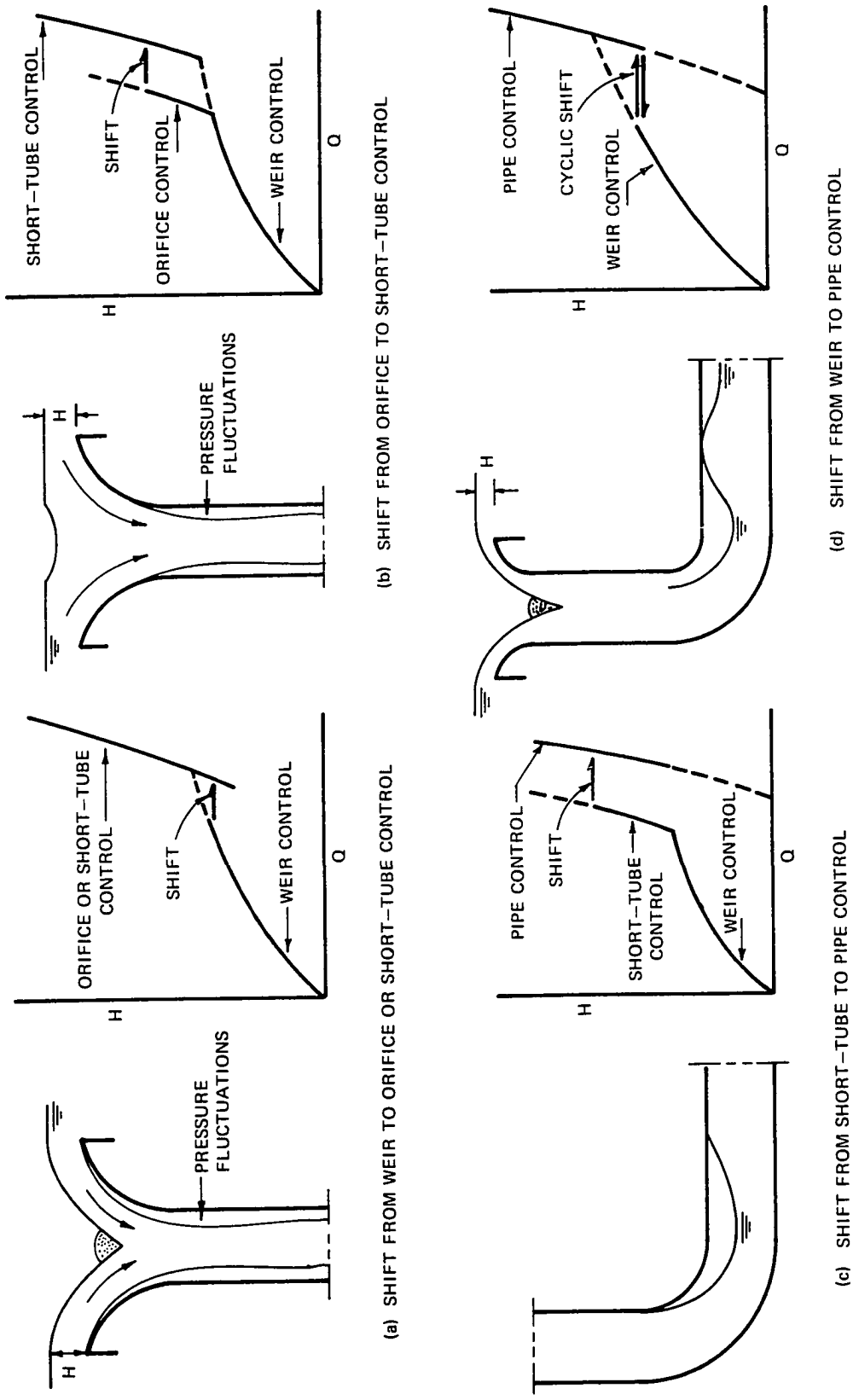

Figure 7. Shift of Flow Control in a Shaft Spillway

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through the shaft, negative pressure develops in the air pockets in the vertical shaft as shown in Figure 7b. Pressure fluctuations that cause vibrations can occur. A sudden shift of control accompanied by an abrupt increase in the dynamic load on the structure is likely to take place as shown in Figure 7b. Vibrations can be eliminated by ventilating the vertical shaft.

(3) Short-tube to Pipe Control. With short-tube control the horizontal conduit flows partly full. The high-velocity water flow drags out the layer of air adjacent to the water surface due to the shear force at the water-air interface as shown in Figure 8a. Air enters from the atmosphere at the outlet portal to replace the outflowing air, resulting in a negative air pressure gradient along the conduit. A shift to pipe control occurs when the water surface touches the roof of the conduit due to the inflowing air current into the conduit and due to the increased amount of water droplets splashing against the roof. The shift of control is accompanied by an increased water discharge (Figure 7c), since the controlling head increases from H_s to h_v as shown in Figure 5, and by an abrupt increase in the dynamic load on the structure. The shift of control can be eliminated by maintaining atmospheric pressure along the horizontal conduit throughout the discharge range by ventilating or by operating the spillway at a discharge below the sealing limit.

(4) Weir to Pipe Control. With crest-weir control the horizontal conduit flows partly full with water-air mixture. The surface of the flow in the conduit is wavy due to the impact of the water falling through the vertical shaft on the floor of the vertical bend.

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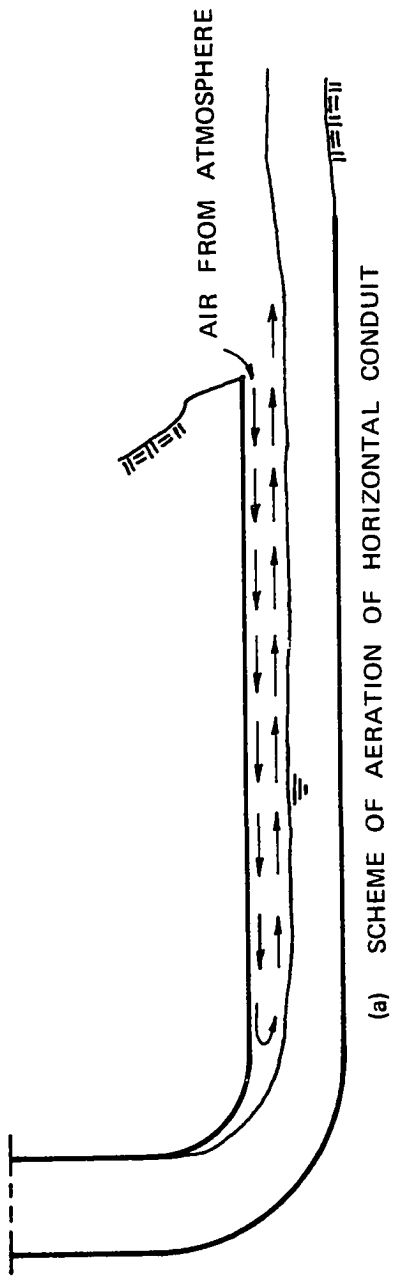

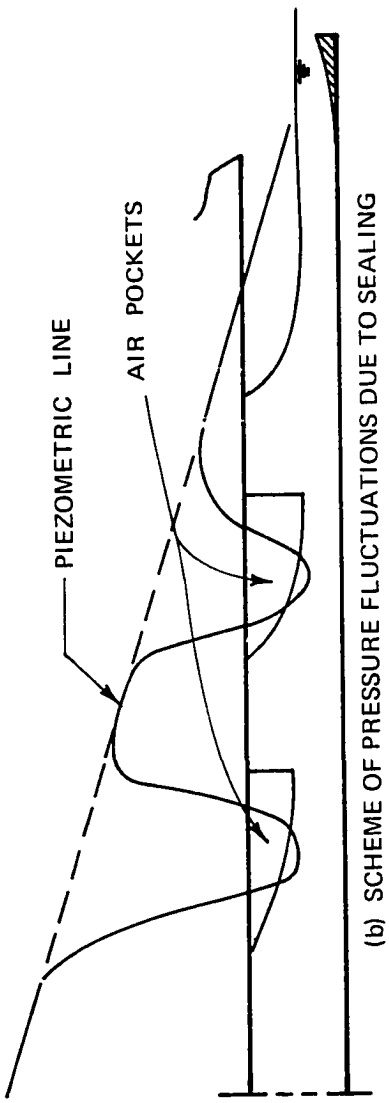

Figure 8. Pressure Fluctuations in the Horizontal Conduit

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As the water waves touch the roof of the conduit, the conduit seals resulting in pressure fluctuations along the horizontal conduit as shown in Figure 8b and in a shift to pipe control accompanied by an increase in water discharge. As the waves "untouch" the roof, a shift back to weir control takes place accompanied by a decrease in water discharge. The reservoir pool elevation remains the same as the water discharge varies. The shift of controls is undesirable because the shift causes vibrations in the structure and variation in the water discharge. Sealing and the subsequent vibrations can be eliminated by maintaining atmospheric pressure along the conduit, by choosing a suitable bend curvature, and by alloting more conduit area than needed for the water flow to allow for the waves and still maintain partly-full flow.

In laboratory hydraulic model studies of shaft spillways, where the reservoir pool is very small, a cyclic shift of controls occurs. The pool elevation fluctuates and the water discharge varies with the shift of control. Figure 9 shows the surging occuring with a flow through a vertical pipe. Figure 10 shows the flow characteristics of the cyclic shift of controls which can occur in hydraulic models of shaft spillways with weir control (Figure 10a) and with short-tube control (Figure 10b). The cyclic shift of controls is accompanied by vibration of the spillway model.

Swaying motion in the horizontal conduit, caused by asymmetric flow entrance conditions at the inlet, can lead to sealing of the conduit and vibration of the structure. The supercritical flow in the circular horizontal conduit appears to slosh back and forth along the conduit. This wave action tends to hasten transition to pipe control.

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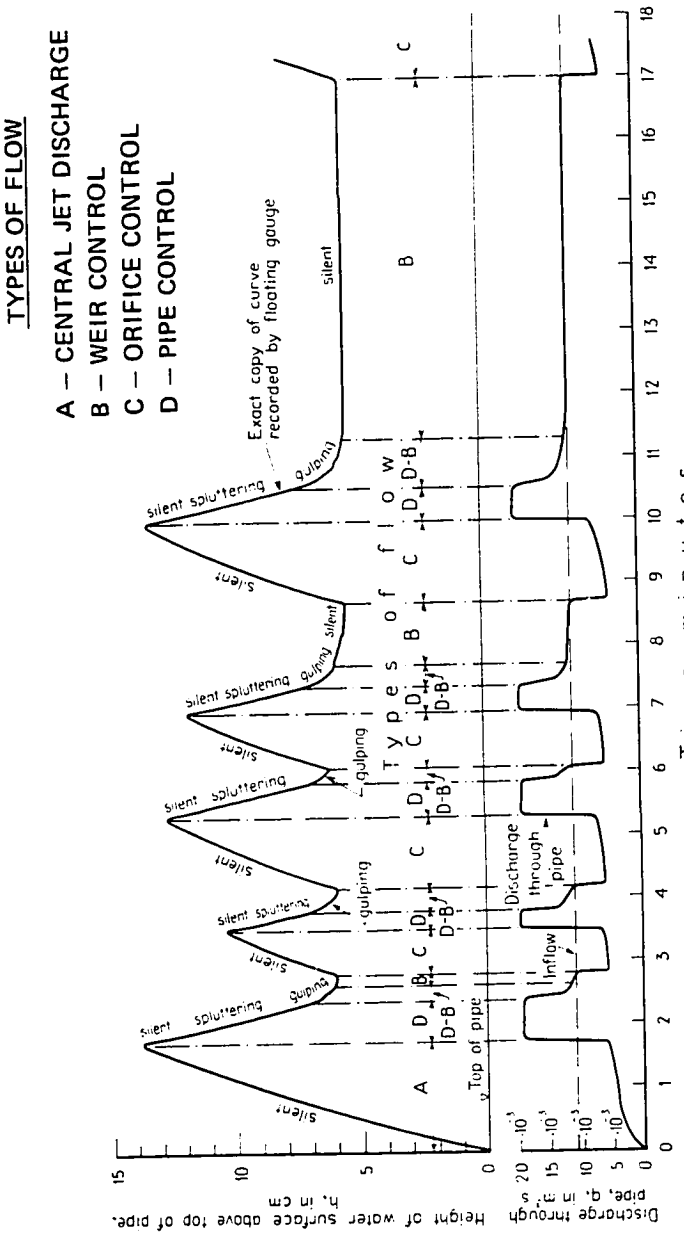

Figure 9. Surging of the Flow into a Vertical Pipe (D = 4 cm) [After Rahm 74/]

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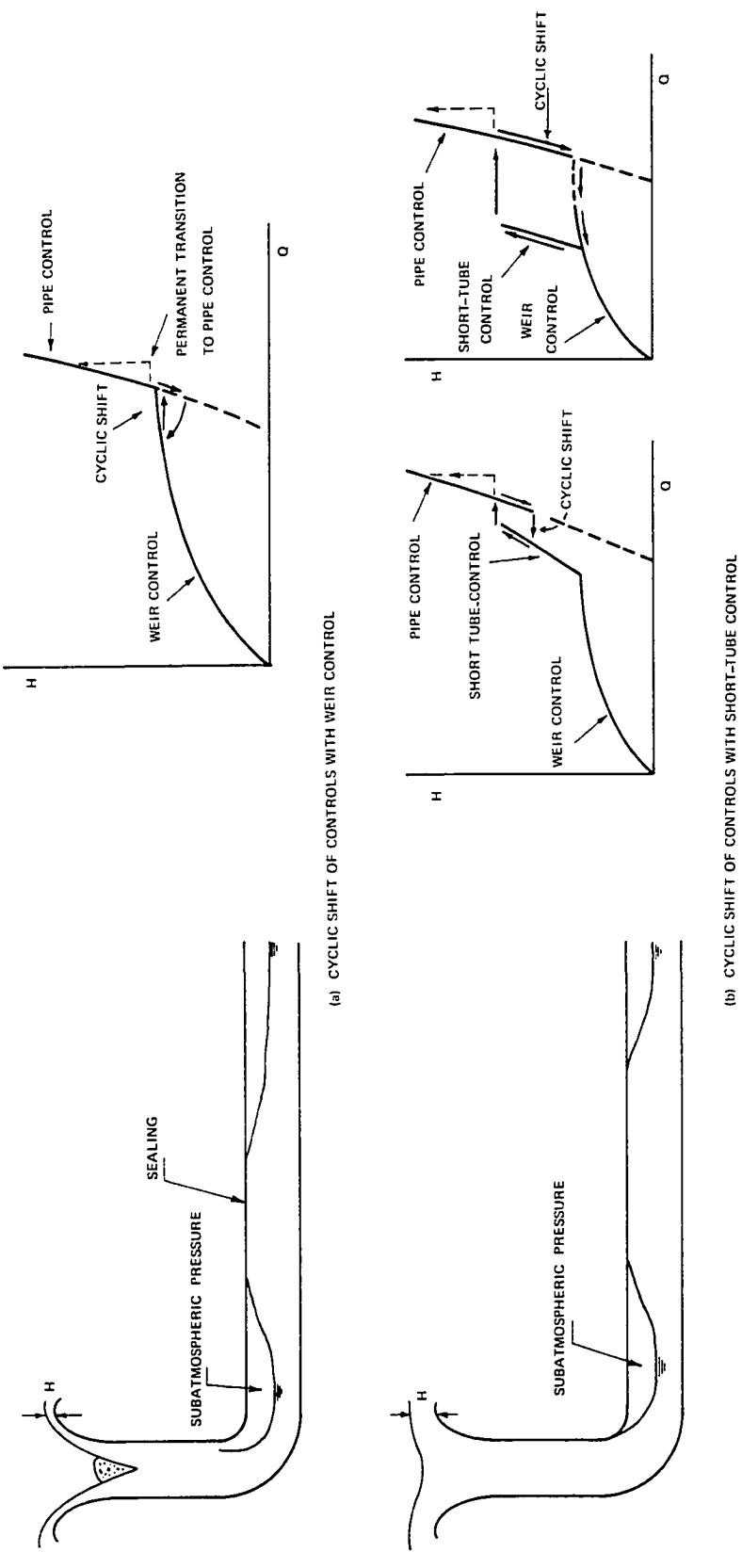

Figure 10. Cyclic Shift of Control in a Shaft Spillway Model

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Wave motion is eliminated by establishing symmetric flow conditions through placing piers at the inlet crest or modifying the topography surrounding the inlet thereby reducing oblique waves in the supercritical flow.

b. Blow Back of Entrapped Air Pockets. Blow back of entrapped air pockets into the vertical shaft are caused by the decrease of the flow discharge as shown in Figure 11.

Vibrations are dangerous when the shaft spillway passes through an earth embankment. Vibrations cause settlement of the earth embankment and the conduit, damage construction joints, and endanger the structural stability of a vertical shaft standing free with its horizontal leg passing through the earth embankment.

3. Clogging

Clogging is caused by the falling of trees and logs through the shaft spillway if the vertical bend is too sharp or the conduit too narrow. Of course, in a well-managed reservoir, log booms will be placed and will be maintained in the reservoir upstream from the spillway inlet.

4. Summary

Sealing or the transition from the free-surface flow to pipe flow in the horizontal conduit is the most undesirable flow characteristic of a shaft spillway. The unsteady flow conditions occuring during sealing can lead to dangerous structural vibrations.

C. Review of Literature

According to available records, the first morning-glory shaft

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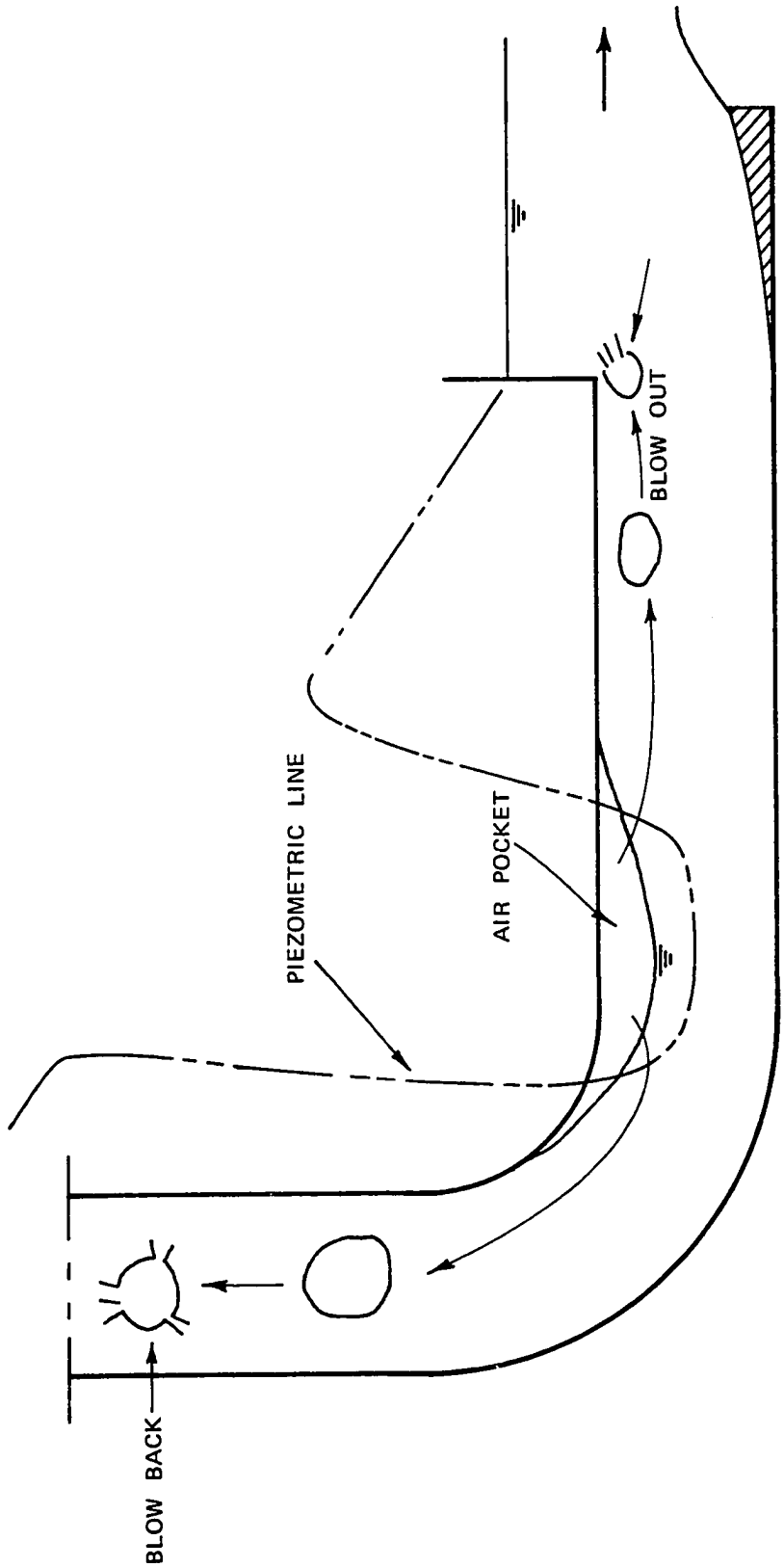

Figure 11. Blow Back and Blow Out of an Entrapped Air Pocket

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spillway was completed in England in 1896. However, the design did not come into general use until the latter part of the 1920's. Since then many shaft spillways have been constructed all over the world. A list of some spillways is given in Table A-1 of Appendix A.

1. General

Several investigators have written about the design of shaft spillways. In 1925, Kurtz 1/ was the first to give a comprehensive discussion of a shaft spillway. Discussion by several prominent engineers 2/ added materially to Kurtz's paper. In 1937, Binnie 3/ gave comprehensive descriptions of seven shaft spillways and the results of model studies. In 1945, Creager, Justin, and Hinds 4/ presented design methods for shaft spillways. In 1956, the American Society of Civil Engineers published a symposium on morning-glory spillways 5,6,7/ in which 18 shaft spillways were described and their operating characteristics discussed. Abecasis 8/ supplemented the ASCE symposium with the description and operating characteristics of three Portugese shaft spillways. In 1958, Blaisdell 9,10,11/ reported model and field tests on closed-conduit spillways used in soil conservation projects. In 1960, the U.S. Bureau of Reclamation (U.S.B.R.) 12/ and in 1955, the Portugese National Civil Engineering Laboratory (L.N.E.C.) 13/ presented comprehensive information for the design of shaft spillways.

2. Design Information

From model studies and prototype observations, design information for the various elements of a shaft spillway have been developed.

a. Inlet. The inlet crest profile is shaped as of an aerated lower nappe over a sharp-crested circular weir. Gourley 14/, Du Pont 15/,

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Camp and Howe 16/, U.S.B.R. 17/, Wagner 6/, Lazzari 18/, Çaklı 19/, and Press 20/ determined experimentally the shape of the crest profile for various flow conditions.

Vortices reduce the discharge capacity 10,21,22,23/. Various anti-vortex arrangements are recommended 3,5,10/. A list of spillways with the anti-vortex arrangements and with other auxiliary elements used is given in Table A-2 of Appendix A.

Submergence of the flow at the inlet crest occurs at a definite ratio of the head over the crest to the crest diameter, H/D_{cr}. The submergence limit was determined by various investigators 6,14,15,16,18, 19,24,25/ and was found to be $H/D_{cr} \cong 0.25$. A list of H/D_{cr} ratio for various spillways is given in Table A-3 of Appendix A.

b. Vertical Shaft. The vertical shaft is designed to accommodate the flow without restrictions and without developing pressures along the sides of the shaft. To avoid negative pressure along the shaft the velocity head, $V^2/2g$, at any section x-x should be equal to or less than the available head, H_x, (pool elevation - elevation of section x-x) 4, 12,13,26,27/. The discharge is equal to $Q = \pi D^2 V/4$, in which D is the diameter of the shaft. Assuming total losses equal to $0.1\ H_x$, the approximate required shaft diameter can be determined as:

$$D \geq 0.408 \frac{Q^{0.5}}{H_x^{0.25}} \qquad (1)$$

Since this equation is for the shape of a falling water jet, the use of the equation results in a convergent-shaped shaft. Because it is impractical to build a conduit with a varying diameter, the vertical shaft

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and the horizontal conduit are ordinarily made of constant diameter. However, no section of the vertical transition or of the vertical shaft should be smaller than that determined by Equation 1. The section at which the constant-diameter shaft intersects the profile determined by Equation 1 forms the throat of the shaft and has the minimum size that can accommodate the flow. Downstream from the throat section the shaft will have an excess of area.

c. Vertical Bend. The vertical bend is usually a 90° - circular bend. Taylor and Elsden 28/ suggested a circular bend whose cross-sectional area increases over the first part of the bend and subsequently decreases. The U.S.B.R. in a standard reference book 12/ suggested:

> Precautions must be taken, however, in selecting vertical or horizontal curvature of the conduit profile and alinement to prevent sealing along some portion by surging or wave action.

The U.S. Bureau of Reclamation used vertical bends of a ratio of the radius of curvature along the centerline to the bend diameter, r/D_b, ranging from 1.04 to 5.5 and the Portugese National Civil Engineering Laboratory used bend curvatures, r/D_b, ranging from 1.2 to 3.2. Bend curvatures used by designers over the world ranged from 0.5 to 5.5 as shown in Table A-3 of Appendix A. As a conclusion, there is no specific design criterion for the curvature of the vertical bend.

d. Horizontal Conduit. The horizontal conduit is designed to flow partly full at all discharges. However, some designers allow the conduit to seal at an intermediate discharge or design the horizontal conduit to flow full throughout the discharge range.

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(1) Partly Full. The conduit size is chosen so that the horizontal conduit flows partly full throughout the discharge range to avoid the possibility of vibrations due to sealing. Various designers recommended partly-full flow in the horizontal conduit, 1,12,13,29,30,31/. Design criteria to avoid sealing of the horizontal conduit were recommended and attempted by some investigators.

The U.S. Bureau of Reclamation in a standard reference book 12/ recommended:

> To allow for air bulking, surging, etc., the conduit size is ordinarily selected so that it will not flow more than 75 per cent full (in area) at the downstream end at maximum discharge.

Since no specific parameters were presented to substantiate such a simple definitive statement, the rule must have been a generalization from specific model studies conducted by the U.S. Bureau of Reclamation.

Engineers of the Portugese National Civil Engineering Laboratory 13/ gave a similar recommendation to that given by the U.S. Bureau of Reclamation except that the area reserved for water was 86 per cent.

Li and Patterson 32/ studied the self-sealing of culverts. Flow through the vertical bend and in the horizontal conduit of a shaft spillway is similar to the flow in a culvert. Li and Patterson found that a culvert seals in three different manners, that is, at a hydraulic jump, due to the backwater curves of either the subcritical or the supercritical flow, and due to the standing surface waves. A shaft spillway flowing at a high Froude number experiences the same phenomenon of sealing by wave action as a culvert. Through theoretical considerations and

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experimental investigations Li and Patterson found a relation to determine the conditions at which a culvert seals:

$$\frac{SL}{B} = \text{function of } \left(\frac{Q}{g\,B^{5/2}} \text{ or } \frac{B}{H_e}, \frac{SB}{n^2}^{1/3}\right)$$

where:

S - longitudinal slope of culvert

L - length of culvert

B - vertical dimension of culvert

g - gravitational acceleration

Q - discharge

H_e - head-water depth, measured from invert at culvert entrance

n - Manning's roughness coefficient

A graph was given to determine sealing.

Carstens 33/ attempted to determine the size of the horizontal conduit flowing partly full. Carstens reviewed the geometric characteristics of eighteen existing shaft spillways. He classified the spillways by Froude numbers computed from the theoretical velocity of water falling from the reservoir pool to the bend, the design discharge, and the assumption of partly-full flow in the horizontal conduit. He found that the Froude number and the ratio of the water-flow area to the total cross-sectional area of the conduit varied over a wide range.

Svankadatta 34/ experimentally studied the limit between a bubbly mixture and pressure flow in the horizontal conduit of a shaft spillway. A single vertical bend was used having a ratio of mean radius of curvature to diameter of 3.3. All of the air was contained in the bubbly mixture.

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Svankadatta did not measure either the air concentration nor the velocity of the flow in the horizontal conduit. Although he used a pressure transducer at the roof at the upstream end of the conduit to determine the discharge at which sealing occurred, sealing could not be observed since his model was opaque. Svankadatta's investigation was the first approach to a systematic study of the phenomenon of sealing.

Table A-3 of Appendix A gives a list of spillways, the Froude numbers, and the ratio of the area of water flow to the area of the conduit at which the spillways were operated. For spillways flowing partly full, the Froude numbers varied from 2.64 to 7.0 and the ratio of the area of water flow to the area of the conduit from 0.28 to 0.93.

As a conclusion, a simple specific design criterion for the sealing limit below which the horizontal conduit of the shaft spillway flows partly full throughout the discharge range is probably impossible inasmuch as sealing is triggered by waves superposed on the supercritical flow in the horizontal conduit.

Blaisdell 10,11/ and Blaisdell and Humphreys 35/ investigated drop-inlet spillways used for agricultural and soil conservation projects in conjunction with low dams. Blaisdell found that spillways controlled by orifice or short-tube flow conditions operated unsatisfactorily with undesirable surging. He recommended spillway operation with weir control and pipe control. The conduit flows partly full for low discharges, slug flow for intermediate discharges, and full for higher discharges. Transition from partly-full to pipe flow may be tolerated in small spillways due to the relatively little damage caused by surging and vibration.

(2) Full. Some designers prefer the horizontal conduit

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to flow full at all discharges 27,36,37,38/. Three arguments for full-conduit flow are presented in the following.

First, from a hydraulic point of view, the high velocity falling water through the vertical shaft meets deeper water in the horizontal conduit whose velocity had been reduced through encountering frictional resistance along the length of the conduit. A hydraulic jump tends to form with considerable dissipation of energy and possible damage to the tunnel lining 37,38/.

Second, high velocity flows cause erosion in the spillway tunnel. A consideration of the power dissipated in the extreme turbulence of the water from the frictional drag of the tunnel lining supports this view 38/. The head loss due to friction is:

$$h_f = \frac{V^2 n^2 L}{2.21\ R^{4/3}},$$

the power dissipated is:

$$P_f = \frac{\gamma h_f Q}{550} = \frac{62.4\ n^2 V^3 L A_c}{550\ R^{4/3}}\ \text{h.p.},$$

and the power dissipated per square foot of wetted perimeter is:

$$P_f = \frac{62.4\ n^2 V^3}{550\ R^{1/3}}\ \text{h.p./sq. ft.} \qquad (2)$$

The power dissipated varies almost with the cubic power of velocity. A conduit flowing full flows with less velocity than when flowing partly full. The reduction in velocity reduces the power dissipated in turbulence

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from the frictional drag of the tunnel lining.

Third, high-velocity flows are liable to cause cavitation. With the conduit flowing full the velocities are reduced 37/.

Williamson 27/ and Young 36/ suggested pipe flow in the horizontal conduit with the inlet flowing submerged at larger discharges for the case of a main spillway. White 37/ and Banks 38/ suggested pipe flow in the horizontal conduit and the vertical shaft without submerging the inlet for a case of an emergency spillway operating to discharge exceptional floods. Various downstream controls have been tried to obtain pipe flow. The most usual being a contracted outlet 36/, although raising the outlet 27,37/ or a combination of these have been tried. With pipe-flow conditions, there is less point in having a smooth bend. A simple right-angled junction offers constructional advantages 37,38/.

e. Outlet. The outlet structure is either a flip bucket or a sloping apron with a stilling basin. Design information is available in literature 12/.

f. Aeration of the Spillway. Air relieves negative pressure, cushions the impact of the falling water 7/, and reduces pitting of surfaces due to cavitation 39/. Spillway designers are at variance concerning the aeration of shaft spillways. Aeration of the water flow ranged from none to some one-third by volume of the water flow 33/. Spillways operated submerged or with pipe control are usually not aerated 27,36,40/. Spillways operated with weir control get adequate aeration from the reservoir pool as shown in Figure 4a, or are aerated through air vents as shown in Figure 4. Some of the spillways of the U.S. Bureau of Reclamation and of the Portugese National Civil Engineering

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Laboratory are vented just downstream from the inlet. Table A-2 of Appendix A gives a list of spillways and indicates where the air vents were placed.

Air demand at the various geometric elements was determined by several investigators:

(1) At the Inlet from the Atmosphere. A. M. Binnie 41/ measured the air entrained by the flow at the inlet of a model and W. J. E. Binnie 3/ reported the results of the air entrainment by the flow at the Burnhope spillway model. The air concentration, Q_a/Q, varied from 100 per cent at weir flow to zero at submerged flow.

(2) At the Vertical Transition. If the crest profile is steeper than for a lower nappe of an aerated flow over a sharp-crested circular weir, negative pressure occurs, and consequently air can be admitted at the vertical transition. Hickox 42/ determined the air demand for the flow over a sharp-crested spillway as:

$$q_a = \frac{(CH)^{3.64} g^{0.5}}{p_a^{1.14}} \qquad (3)$$

where:

q_a - discharge of air per foot length of crest, in cubic feet per second

C - discharge coefficient

H - head over the crest of weir, in ft

g - acceleration of gravity, in ft/sec^2

p_a - reduction of pressure beneath the nappe, in feet of water

Howe, Obadia, and Shieh 43,44/ determined the maximum air demand for a

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sharp-crested weir in relation to flow parameters and found the maximum air demand, Q_a, is 5 per cent of the water discharge, Q.

(3) In the Vertical Shaft. Free falling water into the vertical shaft entrains air with it. Viparelli 45/, Laushey and Mavis 46/, and Jevdjevich and Levin 47/ determined the air demand from experiments on models and found that the air demand depends on the inlet details, on the diameter of the shaft, and on the water level in the shaft. Viparelli found that the air demand for water falling freely in a vertical circular pipe with a hydraulic jump in the shaft is given approximately by:

$$Q_a/Q = 0.022 \left(\frac{Z}{D}\right)^{0.6} \qquad (4)$$

where:

Z - distance from top of shaft to the hydraulic jump

D - diameter of shaft

Laushey and Mavis found that the air demand for spiral flow in the shaft is given approximately by:

$$Q_a/Q = 0.015\ Y \qquad (5)$$

where:

Y - distance of free fall in the shaft to the level of the hydraulic grade line

Curtet and Djonin 48/ studied the downward flow of a mixture of air and water and gave empirical formulas for the flow and concentration conditions.

(4) In the Horizontal Conduit. The horizontal conduit

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is aerated either from the outlet portal or by vents placed below a deflector at the crown of the bend or at the roof of the conduit. Martins 49/ suggested that the capacity of the air vents is the same as the air demand of a hydraulic jump occurring in the conduit downstream of a gate. However, a hydraulic jump is never allowed to take place in the horizontal conduit. The air vent, designed according to Martins suggestion, tends to be oversized. Air demand of a hydraulic jump was determined by model experiments by Kalinske and Robertson 50/ and was found to be:

$$Q_a/Q = 0.0066(F-1)^{1.4} \tag{6}$$

in which F is the Froude number. Campbell and Guyton 51/ from field tests found the air demand of a hydraulic jump at gated outlet works to be

$$Q_a/Q = 0.04(F-1)^{0.85} \tag{7}$$

Similar experiments on models were done by Uppal, Gulati, and Paul 52/, Haindl and Sotornik 53/, and Fasso 54/ and in prototype by Mura, Ijuin, and Nakagawa 55/. Ghetti and Di Silvio 56/ studied the total air demand for outlet works and made some comparisons of the results from model and prototype. The U.S. Bureau of Reclamation measured the air demand at vents below a deflector at the bend in models 57,58/ and prototype 59/. Svankadatta 34/ suggested that the air demand of shaft spillways is the same as of self-aerated open channel flow. Straub and Anderson 60/, Anderson 61/, Straub and Lamb 62/, DeLapp 63/, and Viparelli 64/ determined the air demand of high-velocity flow in models and Hall 65/,

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Michels and Lovely 66/, and Okada, Kudo and Fukuhara 67/ in prototype.

As a conclusion, there is no definite design criterion for the air demand of a shaft spillway in order to avoid sealing of the horizontal conduit and surging of the flow.

3. Model-Prototype Conformance

Shaft spillway models are tested according to model laws. Few prototype tests have been made to check the validity of model tests. Binnie 26/ conducted experiments for the Jubilee shaft spillway with models constructed to scales of 1:19, 1:24, 1:29.4 and 1:43.5. The U.S. Bureau of Reclamation 7,59/ and the Portugese National Civil Engineering Laboratory 8/ made prototype tests on some shaft spillways. The prototype tests confirmed the model tests and showed close agreement in the spillway capacity and performance.

Prototype tests on air demand by the U.S. Bureau of Reclamation 59/ and the Corps of Engineers 51/ showed that the air demand in prototype is greater than in models. The increase in air demand was explained to be due to the increase in turbulence 43,68/. Zanker 69/ suggested the use of the ratio $\mu V / \sigma$ (that is, viscous force/surface tension force) in which:

μ - dynamic viscosity,

V - velocity of water flow,

and

σ - surface tension

as a similarity criterion in studies of air entrainment into water flows.

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4. Problems Involved in Operation and Maintenance of a Shaft Spillway

Difficulties experienced by the U.S. Bureau of Reclamation 70/ and others 5,71/ in the operation and maintenance of shaft spillways are the result of the imposition of dynamic and erosive forces on critical concrete surfaces. Damage occurs to a shaft spillway due to: abrasive erosion of concrete surfaces resulting from the presence of solid matter in the turbulent flow, cavitational erosion caused by negative pressure and by surface irregularities 72/, erosion of the concrete surfaces due to the impact of the falling water and due to the high-velocity flow 73/, and surging of the flow 74,75/ and the subsequent vibrations of the structure 76/. Recommendations for preventive maintenance are to eliminate construction joints in the vertical bend 5/, and to maintain smooth surfaces 5,77/.

5. Summary

Design information for the inlet, vertical shaft, and outlet are available. Knowledge about the problems in operation and maintenance are adequate. However, there is a lack of design information about the geometry of the vertical bend, sealing of the horizontal conduit, and air demand of the shaft spillway.

D. Purpose and Scope of the Investigation

The purpose of this investigation is to study systematically the effect of the various bend and deflector geometries and flow variables on the phenomenon of sealing in order to develop design information whereby the designer can avoid the possibility of a shift to pipe-flow control. A 4-inch square transparent enclosed vertical-shaft spillway

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model is used. The geometric variables are the bend curvature and the deflector at the crown of the bend. Bends in which r/B, where r is the radius of curvature along the centerline and B is the bend dimension, equals 0.5, 1.5, and 2.5 and deflectors at the crown of the bend of thickness t = 1/16 inch, 1/4 inch, and 1/2 inch are used. The parameters of the flow in the horizontal conduit are the Froude number, F, the ratio of the area of the water flow to the area of the conduit, A/A_c, and air concentration in the water flow, Q_a/Q. Air concentrations of Q_a/Q from 0.0 to almost 40 per cent at incipient sealing are varied. The flow conditions in the horizontal conduit are observed visually and are determined experimentally throughout the discharge range until incipient sealing.

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CHAPTER II

EXPERIMENTAL APPARATUS

A. Objective

The objective of the laboratory experiments was to study the phenomenon of sealing, which is the transition from free-surface flow to pipe flow in the horizontal conduit of a vertical-shaft spillway. Sealing with short-tube and with weir control were investigated. The geometric and flow factors affecting sealing were varied systematically. The geometric variables were the bend curvature, r/B, and the deflector. The flow variable was the air concentration in the water flow, Q_a/Q. The Froude number, F, of the free-surface flow in the horizontal conduit and the ratio of the area of the water flow to the conduit area, A/A_c, were determined experimentally throughout the discharge range until incipient sealing. The effect of the above mentioned factors on the pool elevation-discharge relation of a spillway was not evaluated.

In order to study the flow conditions of the free-surface flow in the horizontal conduit with weir-flow control over a range of Froude numbers, F, the water discharge, Q, and the water velocity, V, had to be controlled independently. This control was achieved by variation of the number of water jets which discharged from the supply line down into the vertical shaft.

B. Experimental Apparatus

The experimental measurements were made in a transparent enclosed

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vertical-shaft-spillway model installed in the Hydraulic Laboratory in the School of Civil Engineering of the Georgia Institute of Technology. A general view of the apparatus is shown in Figure 12 and a sketch in Figure 13. A description of the water-flow equipment and the air-supply equipment follows.

1. Water Flow

The water passed through an enclosed vertical-shaft spillway model consisting of a vertical shaft connected to a horizontal conduit by a 90-degree circular bend. The water entered the system through a 6-inch supply line from a constant-head tank as shown in Figure 13. A calibrated 6-inch bend meter was placed in the supply line for water discharge, Q, measurements. The piezometric-head difference across the bend was determined by means of a water differential manometer. A 6-inch gate valve was placed downstream from the bend meter for discharge control followed by a 6-inch tee section which changed the direction of flow from the horizontal to the vertical downward direction. A 1-foot-long 6-inch to 12-inch conical transition connected the tee section to a 12-inch 1-foot-long pipe which terminated in a multiple-tube outlet.

The multiple-tube unit for independent control of water discharge, Q, and velocity, V, is shown in Figures 14, 15, 16, and 17. The multiple-tube outlet consisted of 524 brass tubes soldered in a 3/8-inch thick brass plate and protruding downward from the plate as shown in Figure 17. The tubes were 4-inches long, 3/8-inch in outer diameter, and 1/16-inch in wall thickness. Rubber stoppers were used to plug as many tubes as desired, as shown in Figure 15, thus the water velocity at the tube outlets could be varied independently of the total water discharge. The

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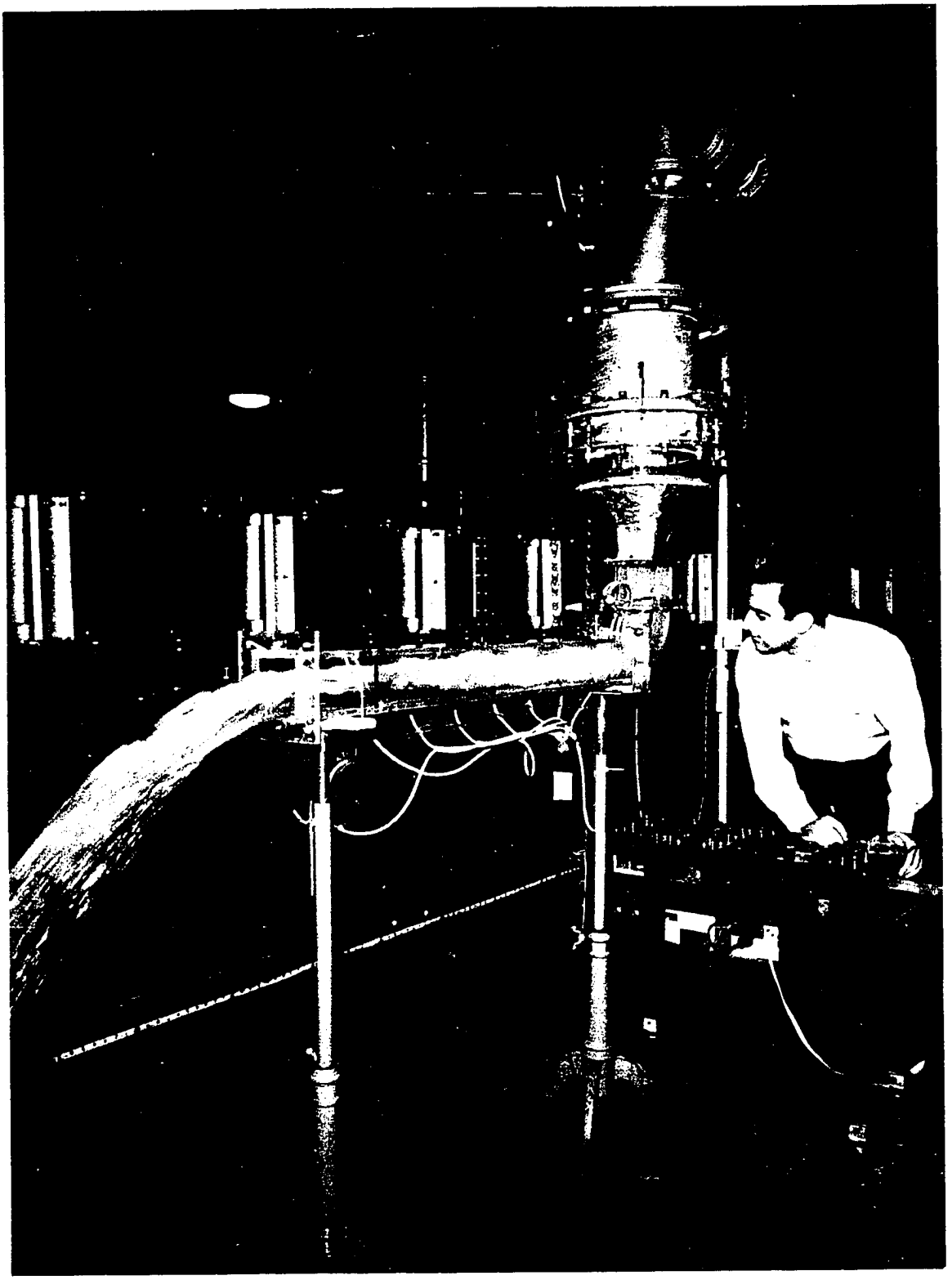

Figure 12. General View of the Vertical-Shaft Spillway Model

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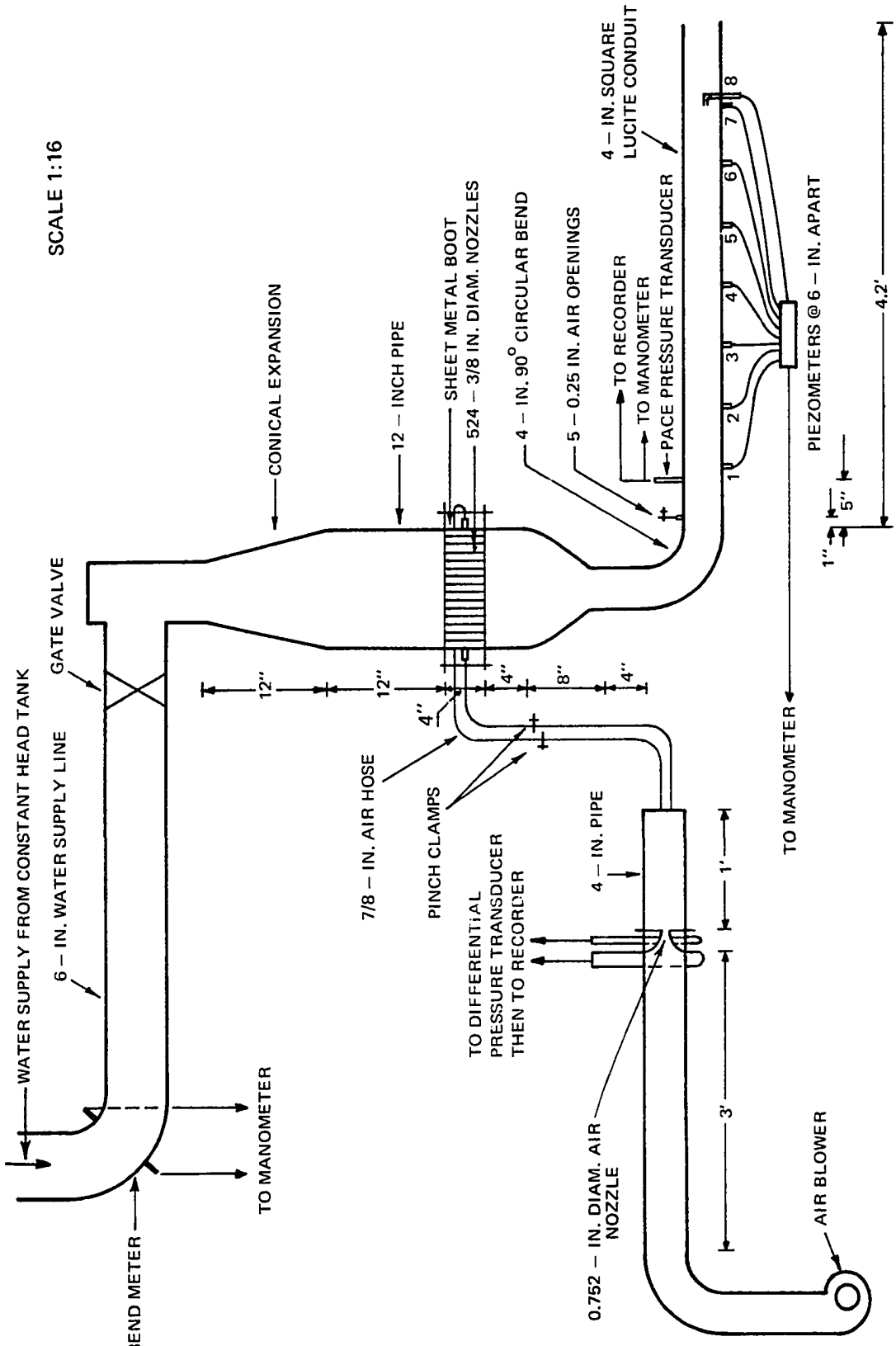

Figure 13. Diagram of the Vertical-Shaft Spillway Model

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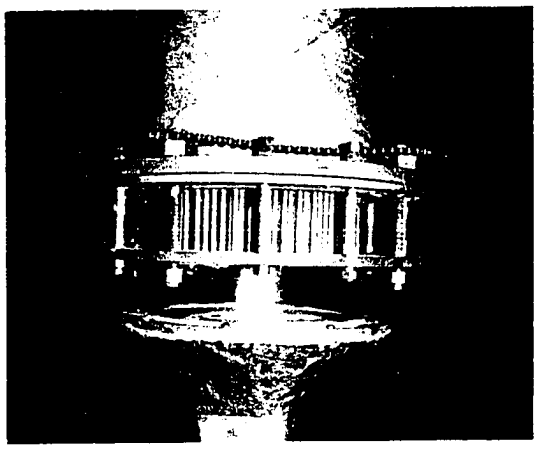

Figure 14. Side View of the Multiple-Tube Outlet

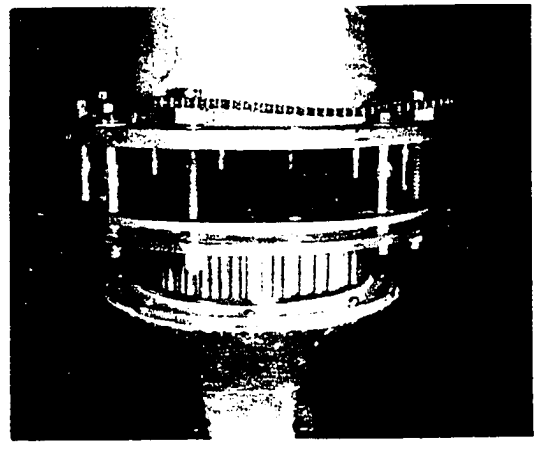

Figure 15. View of the Multiple-Tube Outlet Showing the Rubber Stoppers in Place

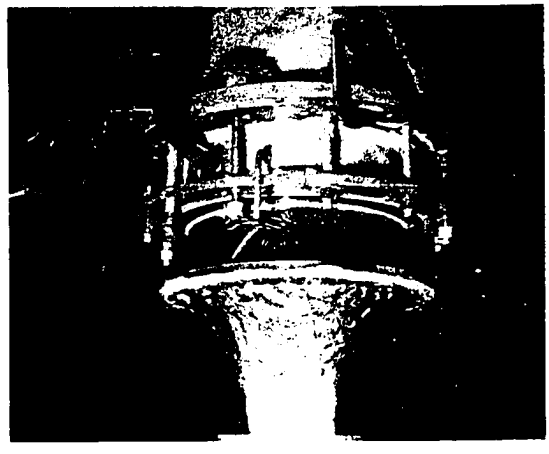

Figure 16. The Air Vents Connected by Hoses to the Air Blower

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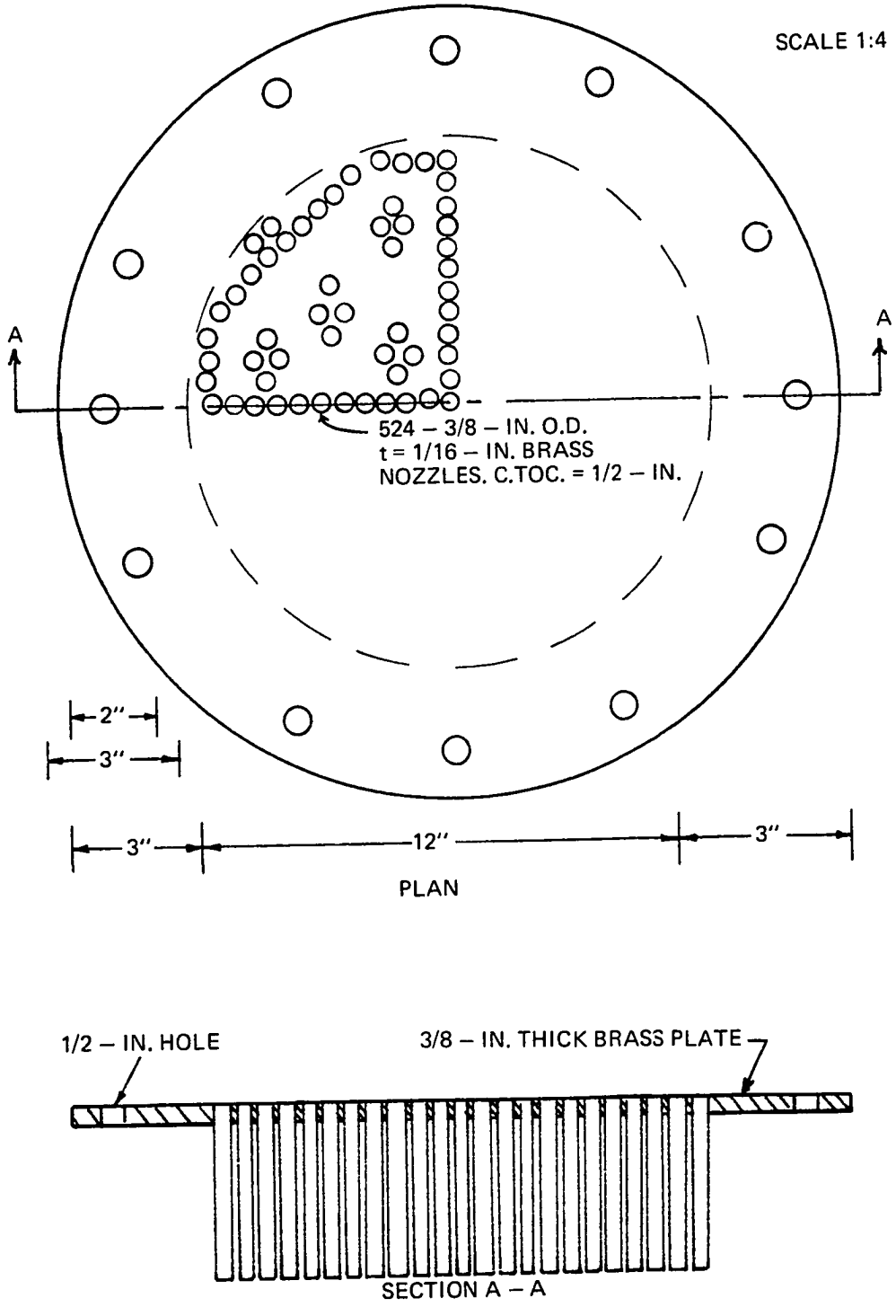

Figure 17. Diagram of the Multiple-Tube Outlet

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brass plate was bolted to the flange of the 12-inch pipe above and connected to the reducer below by 0.5-inch diameter rods. The plate could be moved downward with the aid of sprockets welded over four of the bolting nuts and a chain as shown in Figure 15 in order to change the number of the rubber stoppers.

The vertical shaft could be varied in length from 4 to 14 inches as needed. For short-tube flow the 4-inch-long shaft was used and to simulate weir flow the 14-inch-long shaft was used. Deflectors of thickness of t = 0.00, 1/16, 1/4 and 1/2 inches were inserted at the inner wall of the vertical shaft at the crown of the bend to deflect the flow away from the roof of the horizontal conduit and to enable free-surface flow conditions to prevail.

The bend section connected the vertical shaft to the horizontal conduit. Three 90-degree circular bends with r/B = 0.5, 1.5, and 2.5 were tested.

The horizontal conduit was the main testing section where the phenomenon of the transition from free-surface to pipe flow, or sealing, occurred. The conduit was 4-inch square in cross section. A 4.2-feet-long conduit was used with short-tube flow control and a 6.2-feet-long conduit was used with weir-flow control. The horizontal conduit was equipped with 7 floor piezometers, 1/16-inch in diameter, as shown in Figure 18, placed 6-inches apart and one movable stagnation tube made of a hypodermic needle 0.025-inch in outer diameter and 0.020-inch in inner diameter. The tip of the stagnation tube was in the same cross section as the downstream floor piezometer. The piezometers and the stagnation tube were connected to an open-column manometer. At the

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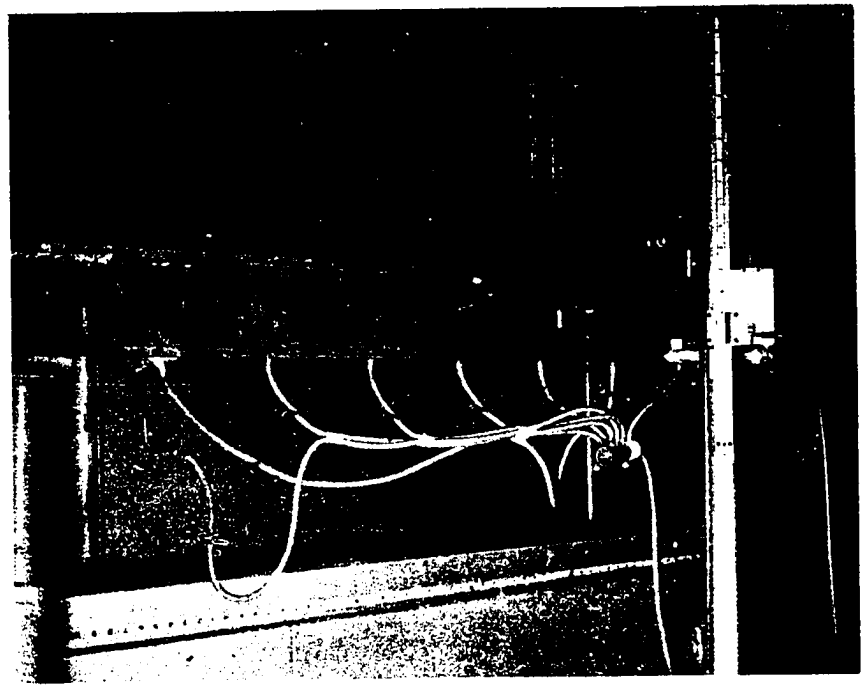

Figure 18. The Horizontal Conduit with the Piezometric Openings, Stagnation Tube, and Manometer

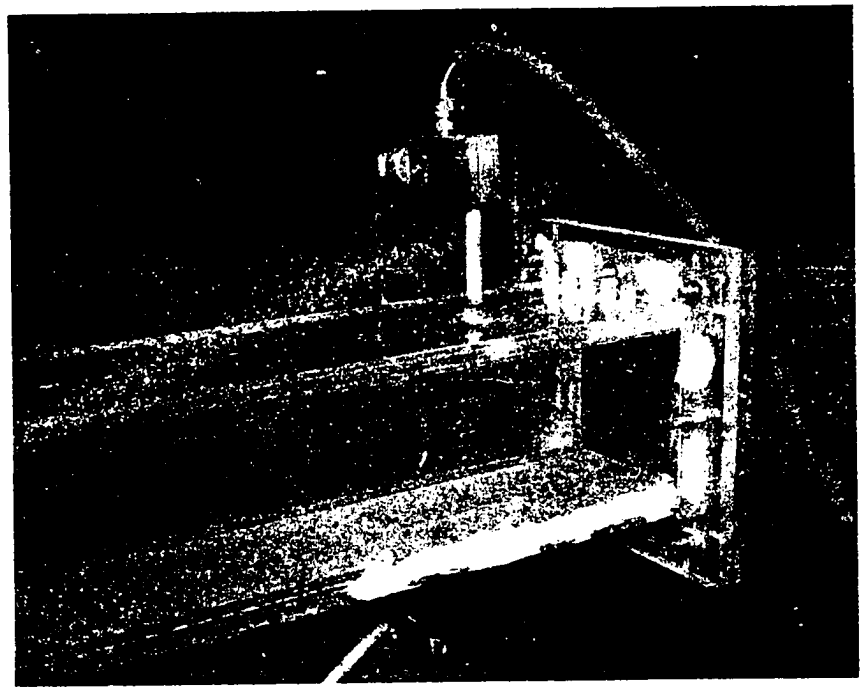

Figure 19. The Pressure Transducer and the Air Vents on the Roof of the Conduit

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roof of the horizontal conduit five 1/4-inch air vents were installed in a row across the conduit roof. The row of vents was located one inch from the upstream end of the horizontal conduit as shown in Figure 19. A short piece of rubber tubing was attached to each vent so that each vent could be opened or closed by pinch clamps in order to admit air from the atmosphere to the conduit. A deflector 1-inch thick and 6-inches long was inserted on the roof at the upstream end of the conduit to study the deflector effect on sealing. A Pace pressure transducer was placed on the roof 5 inches from the upstream end of the conduit. The transducer was mounted on a 3-inch-long metal tube as shown in Figure 19. The Pace pressure transducer model KP15 is a diaphragm type in which the pressure is sensed through the deflection of a flat magnetic stainless diaphragm located between two magnetic pickup coil assemblies. Motion of the diaphragm results in a change in the inductance ratio between the pickup coils to produce an output voltage proportional to the pressure. The output signals from the pressure transducer were amplified and recorded on a two-channel Sanborn writing oscillograph model 60-1300. The oscillograph unit is shown in Figure 20. The pressure transducer could be connected to a water manometer, shown in Figure 21, for calibration of the transducer during each run.

2. Air Supply

Air discharge, Q_a, was a variable in the experiments. The air was supplied by an air blower. The air passed through a series of pipes, nozzle, and rubber hose (Figure 22), entered the enclosed spillway model downstream of the multiple-tube outlet, and mixed with the water in the reducer section as shown in Figure 16.

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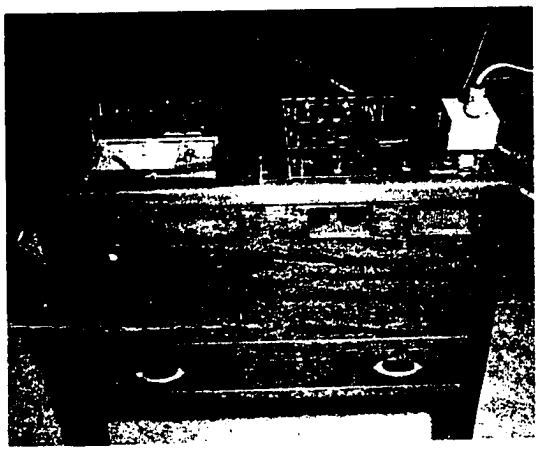

Figure 20. The Two-Channel Sanborn Writing Oscillograph

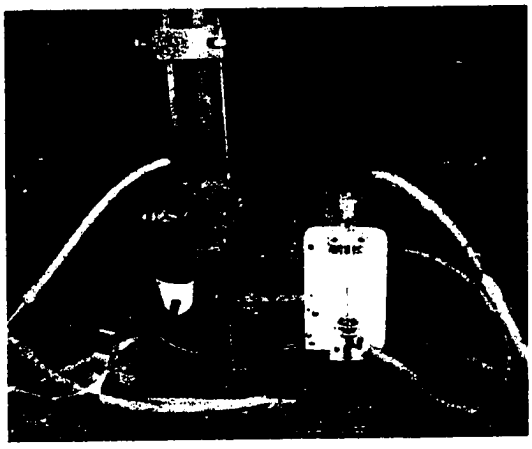

Figure 21. The Water Manometer for the Calibration of the Transducers

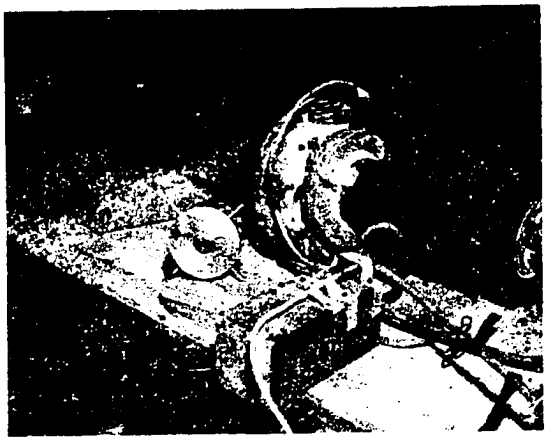

Figure 22. The Air Measuring Instruments Showing the Air Nozzle and the Differential-Pressure Transducer

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A straight 3-foot-long 4-inch-diameter copper pipe was connected to the air blower and was followed by an aluminum smooth nozzle for air discharge measurement. The throat diameter of the nozzle was 0.755 inches. Piezometers at the upstream end and throat sections of the nozzle were connected to a Sanborn differential pressure transducer model 266B as shown on Figure 22. The transducer was of a diaphragm type and was connected to a two-channel Sanborn direct writing oscillograph through an amplifier. The transducer could also be connected to the water manometer, shown in Figure 21, for calibration of the transducer during a run. A 1-foot-long copper pipe followed by three 12.5-foot-long 1-inch-diameter rubber hoses connected the nozzle to the enclosed spillway model. Pinch clamps on the rubber hoses controlled the amount of air discharge admitted to the spillway. The air entered the spillway model through three air vents 1-inch in diameter drilled into the sheet metal, which was inserted in the 4-inch gap between the 12-inch water supply pipe and the reducer around the multiple-tube outlet as shown in Figure 16. Silastic rubber adhesive was used to seal the small spaces between the sheet metal and the flanges of the 12-inch pipe above and the reducer below to make the enclosed spillway model air tight.

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CHAPTER III

EXPERIMENTAL PROCEDURE

The experimental investigation consisted of the study of the factors affecting the transition from short-tube to pipe control and the transition from weir to pipe control. The transition from free-surface flow to pipe flow in the horizontal conduit is called sealing. An experimental run consisted of setting up a combination of variables, calibration of instruments, and measurement of the flow characteristics and observation of the flow conditions.

A. Setup of a Run

The geometric and flow factors were varied systematically in order to evaluate the effect of each variable on the flow conditions in the horizontal conduit and on the phenomenon of sealing. The systematic setup of the variables at short-tube and at weir control follows.

1. Short-tube Control

a. Bend. Bends of r/B = 0.5, 1.5, and 2.5 were tested. No deflector was inserted at the crown of the bend nor was air entrained into the water.

b. Deflector. Deflectors of thickness t = 1/16 inch, 1/4 inch, and 1/2 inch were inserted at the crown of the bend and a deflector of thickness t = 1 inch was inserted on the roof at the upstream end of the horizontal conduit. The deflectors at the crown of the bend were inserted in combination of each bend while the deflector at the upstream

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end of the horizontal conduit was inserted downstream of the bend of r/B = 1.5 only.

c. Air. Various amounts of air were entrained into the water. An air discharge was entrained with each combination of bend and deflector.

2. Weir Control

a. Number of Water Jets. The number of jets discharging into the vertical shaft was varied to simulate the effect of crest-weir control on the water velocity in the horizontal conduit.

b. Air. Various amounts of air were entrained into the water to simulate the effect of aeration from the reservoir pool surface.

c. Bend. Bends of r/B = 0.5, 1.5, and 2.5 were tested with each combination of air concentration and number of water jets. No deflector was inserted.

d. Deflector. A deflector of thickness t = 1/2 inch was inserted at the crown of the bend in combination of each bend, air concentration, and number of water jets. A deflector of thickness t = 1 inch was inserted at the upstream end of the horizontal conduit in combination with the bend of r/B = 1.5 only.

B. Calibration of Instruments

Prior to and after each experimental run, the pressure transducers on the horizontal conduit and at the air nozzle were calibrated. The connection arrangements of the pressure transducers to the water manometer and to the oscillograph are shown in Figure 23. Negative pressures were applied to both transducers by changing the water level

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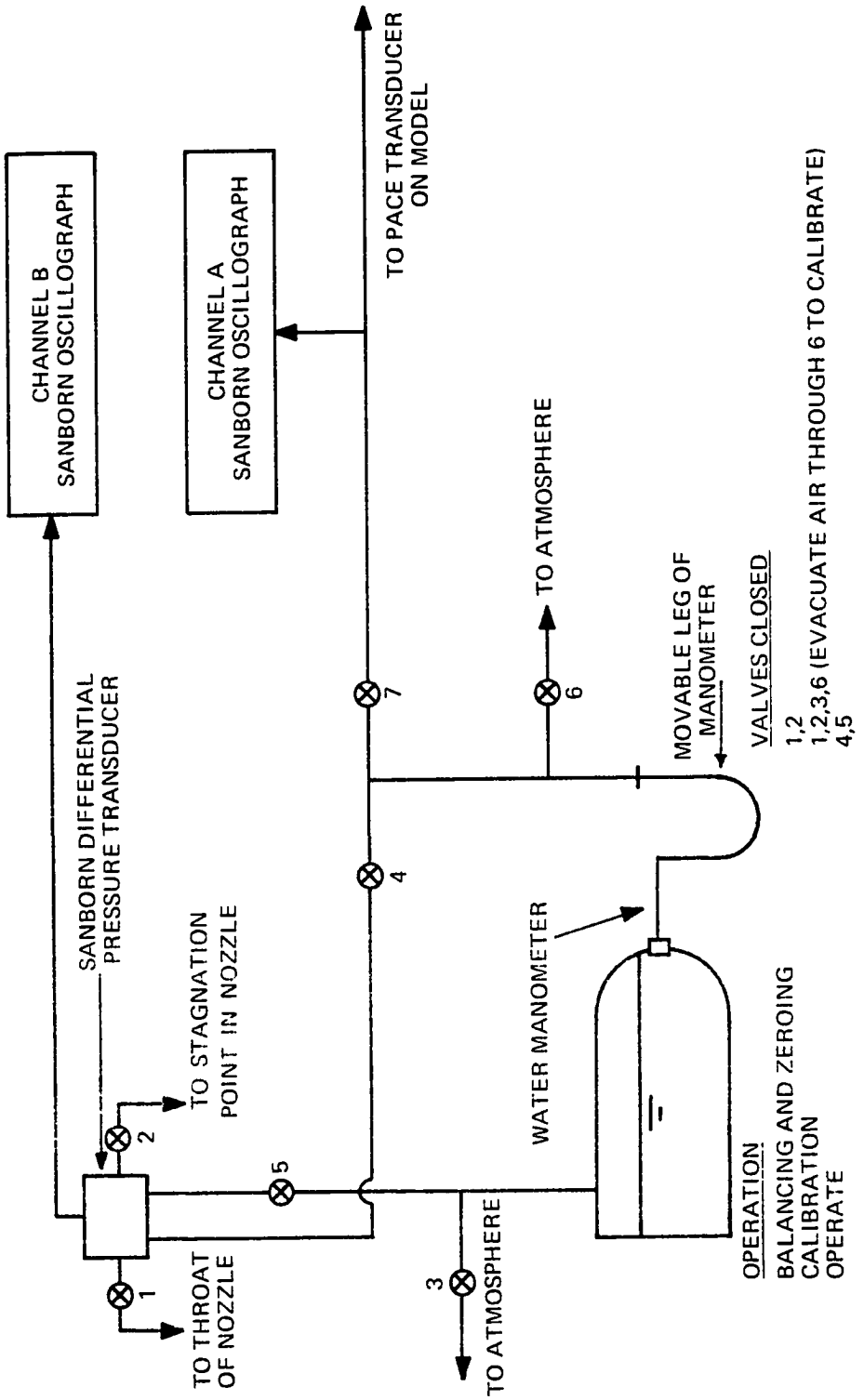

Figure 23. The Connections of the Transducers

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in the manometer. Calibration traces were then recorded on the oscillograph chart together with the corresponding manometer deflections. A typical calibration curve is shown in Figure 24.

C. Measurement Procedure

During a run the following experimental procedure was followed. The control valve on the water supply line was opened. The deflections of the differential water manometer connected to the bend meter in the water-supply line were determined and recorded. A reading of the piezometer heads of the stagnation tube, situated at approximately 0.6 the depth of non-aerated flow and just in the clear water section in aerated flow, and of the static piezometer on the floor of the conduit were determined on the open-column water manometer and recorded. For non-aerated flow the depths of water flow at the section of the stagnation tube was measured by means of a scale and recorded. Pressure records of the conduit transducer and of the air transducer were traced on the oscillograph chart. The control valve was opened further in many steps covering all the water discharge range of the free-surface flow in the horizontal conduit till transition to pipe flow, or sealing, occurred. At incipient-sealing and at sealing conditions the piezometric heads along the horizontal conduit were determined.

Incipient-sealing and sealing conditions were determined more than once as a check. Supplementary runs were made with the air vents on the roof of the conduit open to evaluate the vent effect on sealing.

Sealing was decided upon with the aid of visual observation of the pressure record on the roof of the horizontal conduit, and of the

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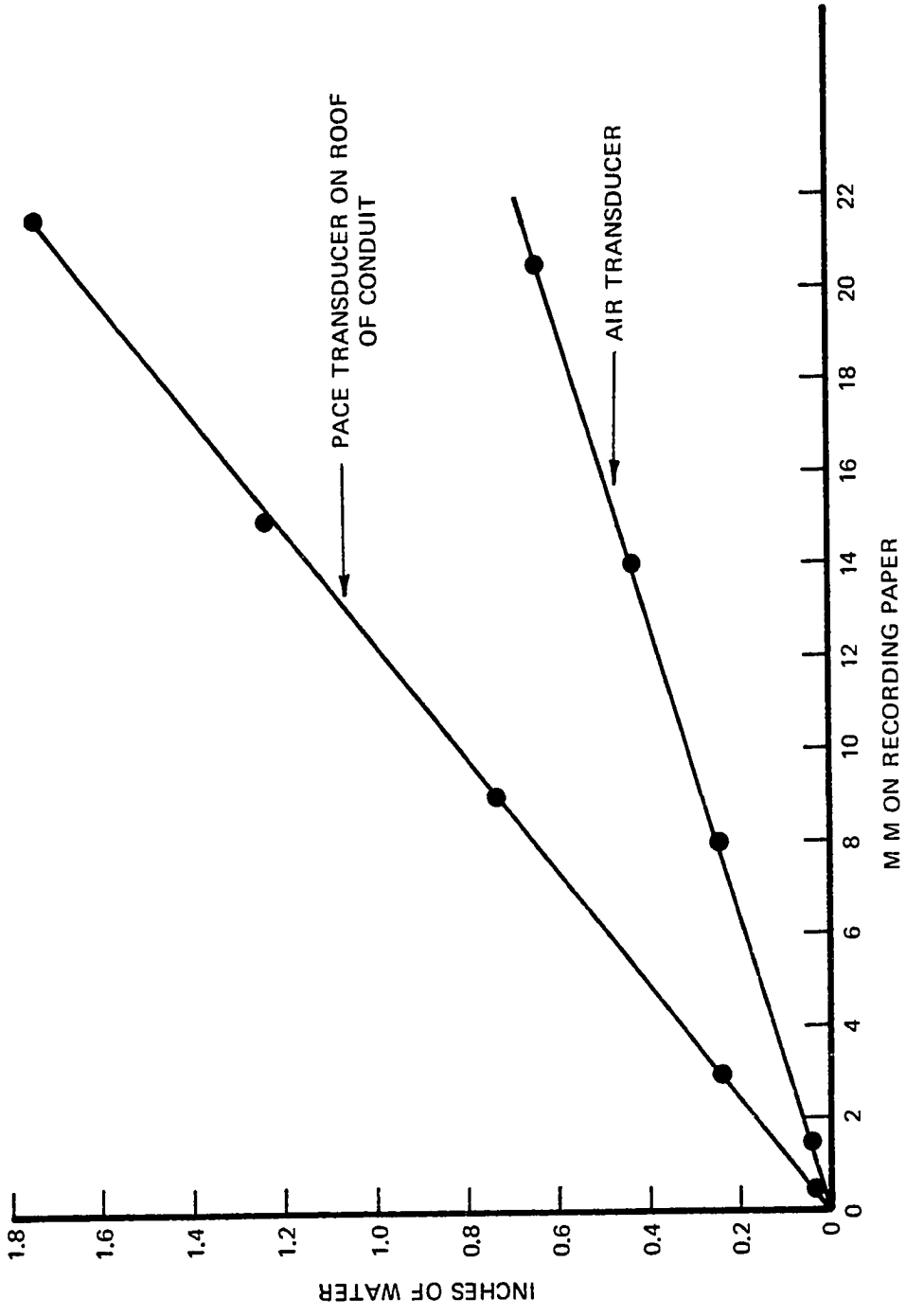

Figure 24. Typical Calibration Curves of the Transducers

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piezometric-pressure readings along the floor of the conduit. Sealing occurs when the pressure on the roof as recorded by the oscillograph becomes positive and when the piezometric-head elevation at any section along the conduit is above the elevation of the roof of the conduit. A typical pressure record and piezometric-head elevations along the floor of the conduit at incipient-sealing and at sealing conditions are shown in Figure 25.

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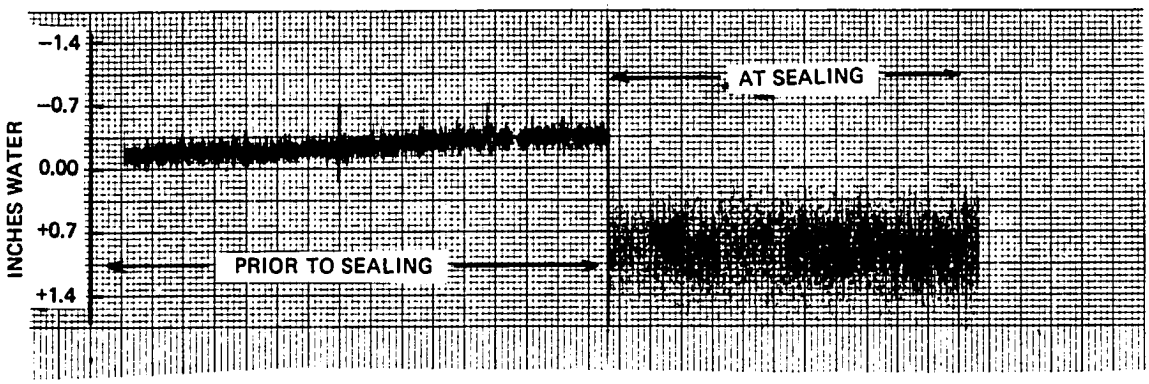
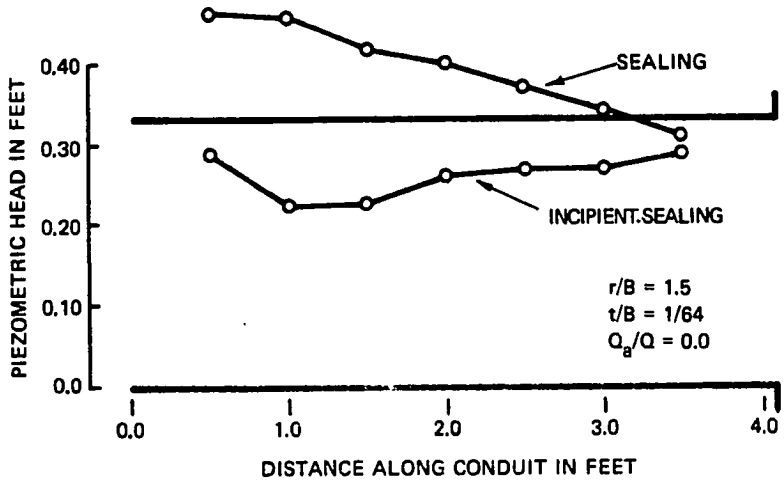


(a) PRESSURE RECORD OF TRANSDUCER AT ROOF



(b) PIEZOMETRIC HEAD ELEVATION ALONG CONDUIT

Figure 25. Typical Pressure Records at the Roof of the Horizontal Conduit and Piezometric-Head Elevations Along the Conduit at Incipient-Sealing and at Sealing Conditions

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CHAPTER IV

ANALYSIS OF EXPERIMENTAL RESULTS

In this chapter the experimental results are presented and analyzed. Experimental data from other model studies and data of existing shaft spillways are also analyzed to verify the results of this experimental investigation. The flow conditions at weir and at short-tube control and the transition from weir to orifice control, from short-tube to pipe control, and from weir to pipe control are discussed.

A. Transition from Weir to Orifice Control

Inasmuch as this experimental investigation did not include the study of the transition from weir to orifice control, data obtained from other model studies are analyzed and presented.

1. General

If the purpose of a dam is flood control, irrigation, or public or industrial water supply, where the discharge is to be limited in the river downstream from the dam, the shaft spillway is designed to operate submerged at higher discharges. Submergence can be achieved by transition to orifice control as shown in Figures 5b and 6b. Of the ninety-six shaft spillways reviewed in Table A-3 of Appendix A, seventeen vertical-shaft spillways operated submerged at design capacity.

The discharge equation for weir control is:

$$Q = C\, D_{cr}\, g^{0.5}\, H^{1.5} \qquad (8)$$

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in which C is a discharge coefficient, D_{cr} is the crest diameter, and H is the total head over the crest. The discharge equation for orifice control with the inlet of the shaft submerged is:

$$Q = C_o A_o \sqrt{2gH_o} \tag{9}$$

in which C_o is a discharge coefficient, A_o is the cross-sectional area at the vertical transition throat, and H_o is the total head at the throat section.

2. Submergence Limit

Camp and Howe 16/, Wagner 6/, White and McPherson 6/, Blaisdell 10/, Lazzari 18/, Bunt 24/, and Çatakli 19/ experimentally determined the submergence limit, H/D_{cr}, at which the transition from weir to orifice flow occurs in circular sharp-crested weirs. The submergence limit was found to be affected by the approach velocity at the crest, by the pressure under the lower nappe of the flow, and by vortices. The submergence limit, H/D_{cr}, increases as the approach velocity decreases and as the pressure under the lower nappe decreases as shown in Figure 26. The submergence limit, H/D_{cr}, as found by the above mentioned investigators is as follows:

Wagner	0.225
White and McPherson	0.30
Blaisdell	0.235 - 0.245
Lazzari	0.25
Camp and Howe	0.25
Çatakli	0.245
Çatakli	0.35

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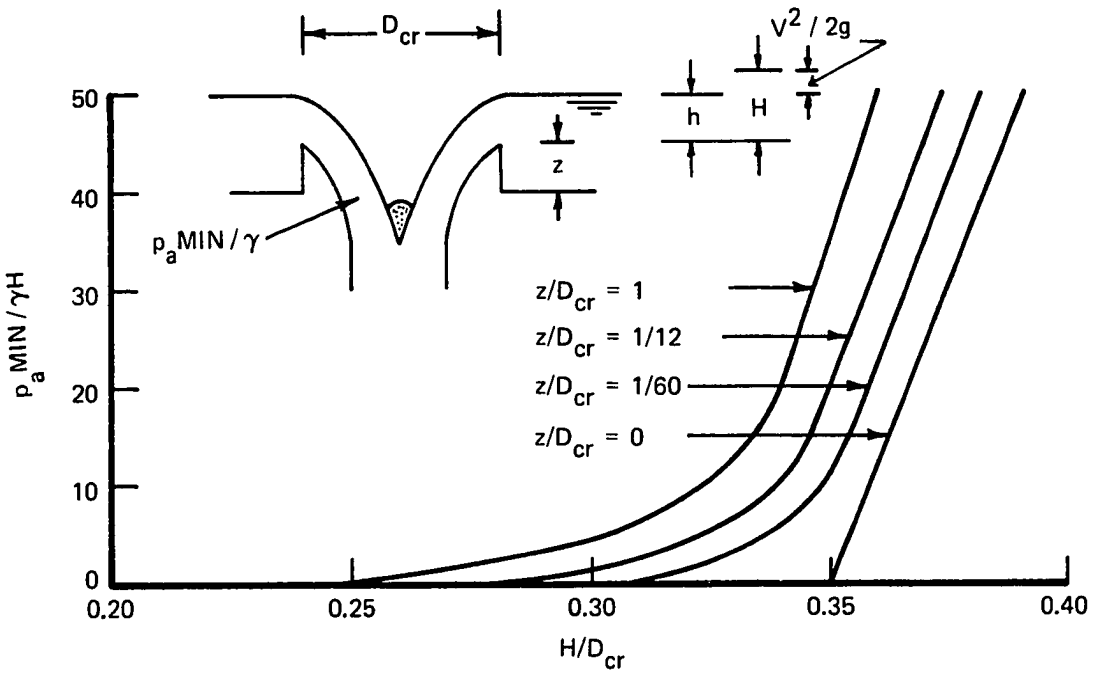

Figure 26. Effect of Pressure Under Nappe and Approach Velocity on Submergence Limit of a Shaft-Spillway Inlet [After Cataklı 19/]

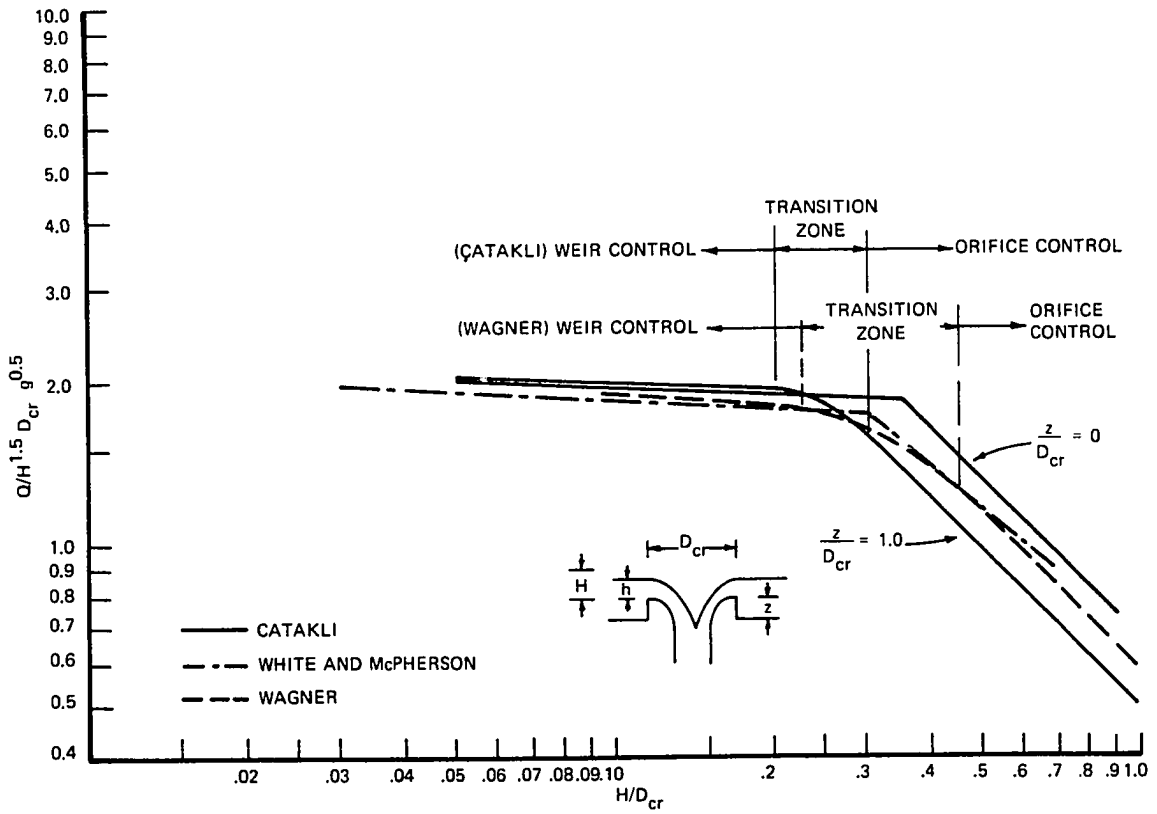

Figure 27. Submergence Limit of Flow over a Sharp-Crested Circular Weir [After Wagner 6/ and Cataklı 19/]

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Wagner and Çaklı showed that there exists a transition zone between weir and orifice control as shown in Figure 27.

Shaft spillways will not submerge at the same submergence limit, H/D_{cr}, since the transition from weir to orifice control is affected by the proportioning of the other geometric elements as was explained on Figure 6. Flow through 15 shaft spillways of Table A-1 of Appendix A were analyzed and their submergence limit determined as shown in Figure 28. Few spillways submerged at H/D_{cr} equal to 0.20 - 0.30, the rest submerged at H/D_{cr} less than 0.20 indicating the effect of the other geometric elements such as the shaft diameter, the throat diameter, or the deflector.

If the crest profile is steeper than of a lower nappe of flow over a sharp-crested circular weir, pressure fluctuations accompanied by vibrations and a sudden shift of control can occur as is shown in Figure 7a.

3. Air Demand

Air is entrained into a shaft spillway from the reservoir pool by the downward flowing water as shown in Figure 4a. Air can also be entrained at the vertical transition in case the vertical transition profile is shaped steeper than for an aerated lower nappe flow over a sharp-crested circular weir or at below a deflector inserted at the throat of the transition as shown in Figure 4b. The dimensionless parameter, Q_a/Q, where Q_a is the air discharge and Q is the water discharge, can be used in relation with other flow parameters to formulate the air demand.

a. From the Reservoir Pool. Few investigations have been made

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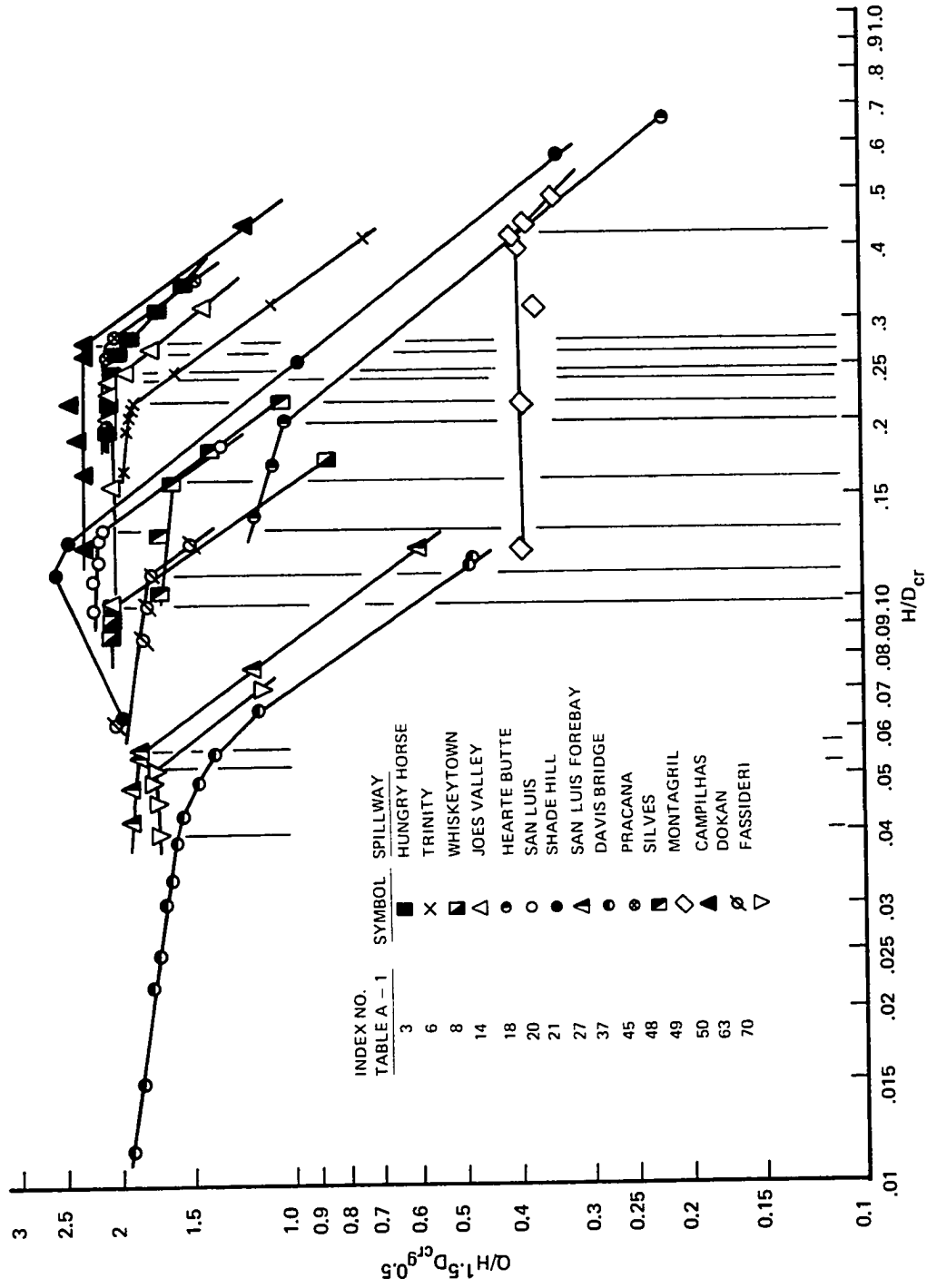

Figure 28. Submergence Limit of Existing Shaft Spillways

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to determine the amount of air entrainment by the water flow from the reservoir pool. The amount of air entrained by the Burnhope shaft spillway model 3/ is shown in Figure 29a, by the water flow through a 1-inch diameter sharp-ended pipe 41/ is shown in Figure 29b, by the water flow through a 1-inch diameter pipe with a trumpet-shaped entrance 5-inch in diameter 41/ is shown in Figure 29c, and by the water flow through 4-inch and 6-inch diameter shaft spillway models 78/ are shown in Figures 29d and 29e, respectively. No conclusive relation between the ratio of air discharge to water discharge, Q_a/Q, and flow parameters could be formulated. A similarity criterion for air entrainment into water flow does not exist at present 69/, though some studies are under way 79/. The above mentioned air demand ratios can only be used qualitatively in the absence of a similarity criterion. Air-discharge to water-discharge ratios, Q_a/Q, varied from over 100 per cent at low water flows with weir control to zero per cent with orifice control.

b. At the Vertical Transition. The air demand, Q_a, for flow over a sharp-crested weir was determined by Hickox 42/ and Obadia and Shieh 43/. Plots of the parameter Q_a/Q versus flow and geometric parameters are shown in Figure 30.

The maximum air demand ratio, Q_a/Q, for sharp-crested weir was found to be approximately 5 per cent. The U.S. Bureau of Reclamation 7/ measured the air demand through air vents at the vertical transition for Hearte Butte shaft spillway and found that the maximum air demand, Q_a/Q, was 5 per cent in the model and 20 per cent in the prototype (Figure 30d).

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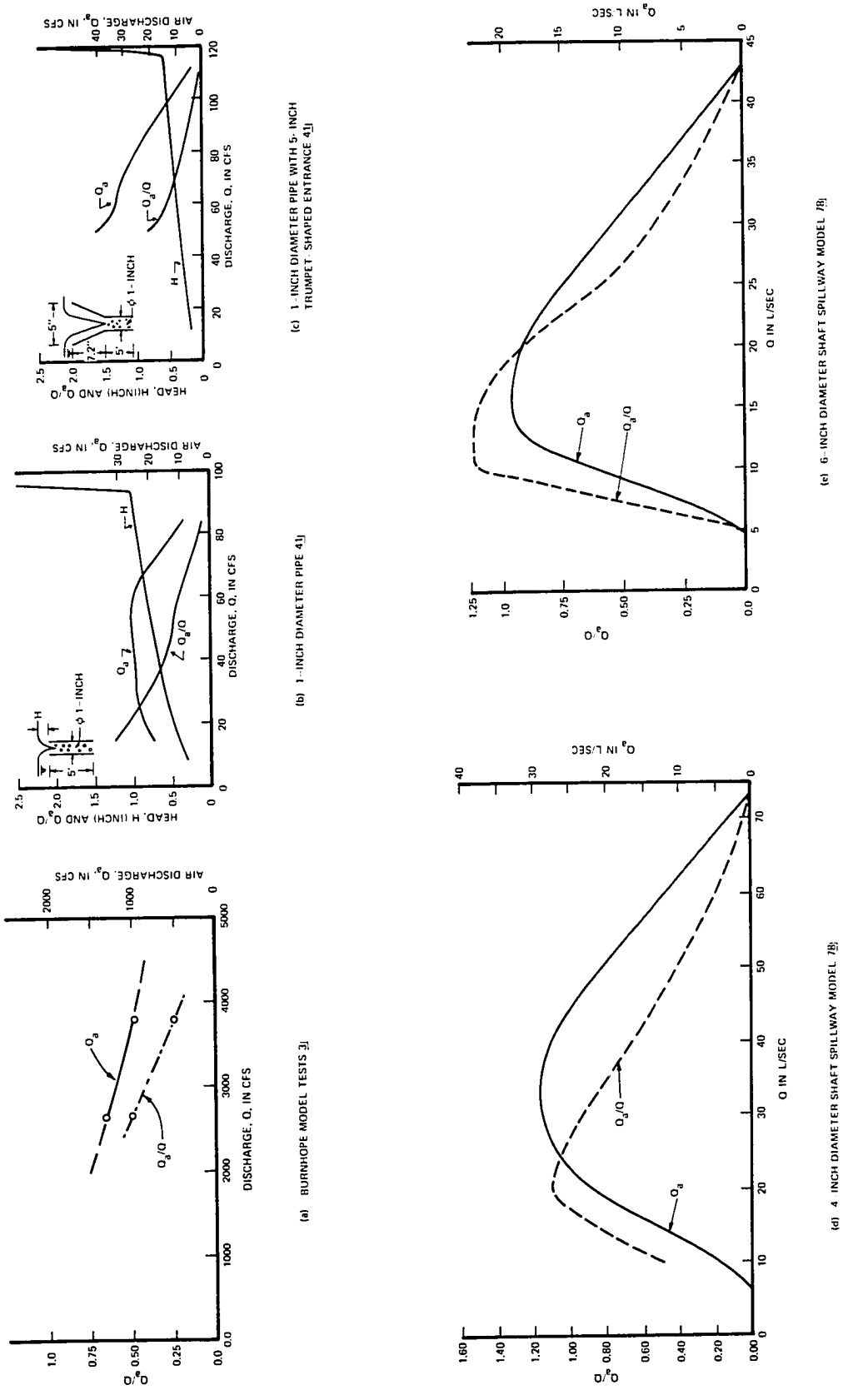

Figure 29. Air Demand from the Pool Surface of a Shaft

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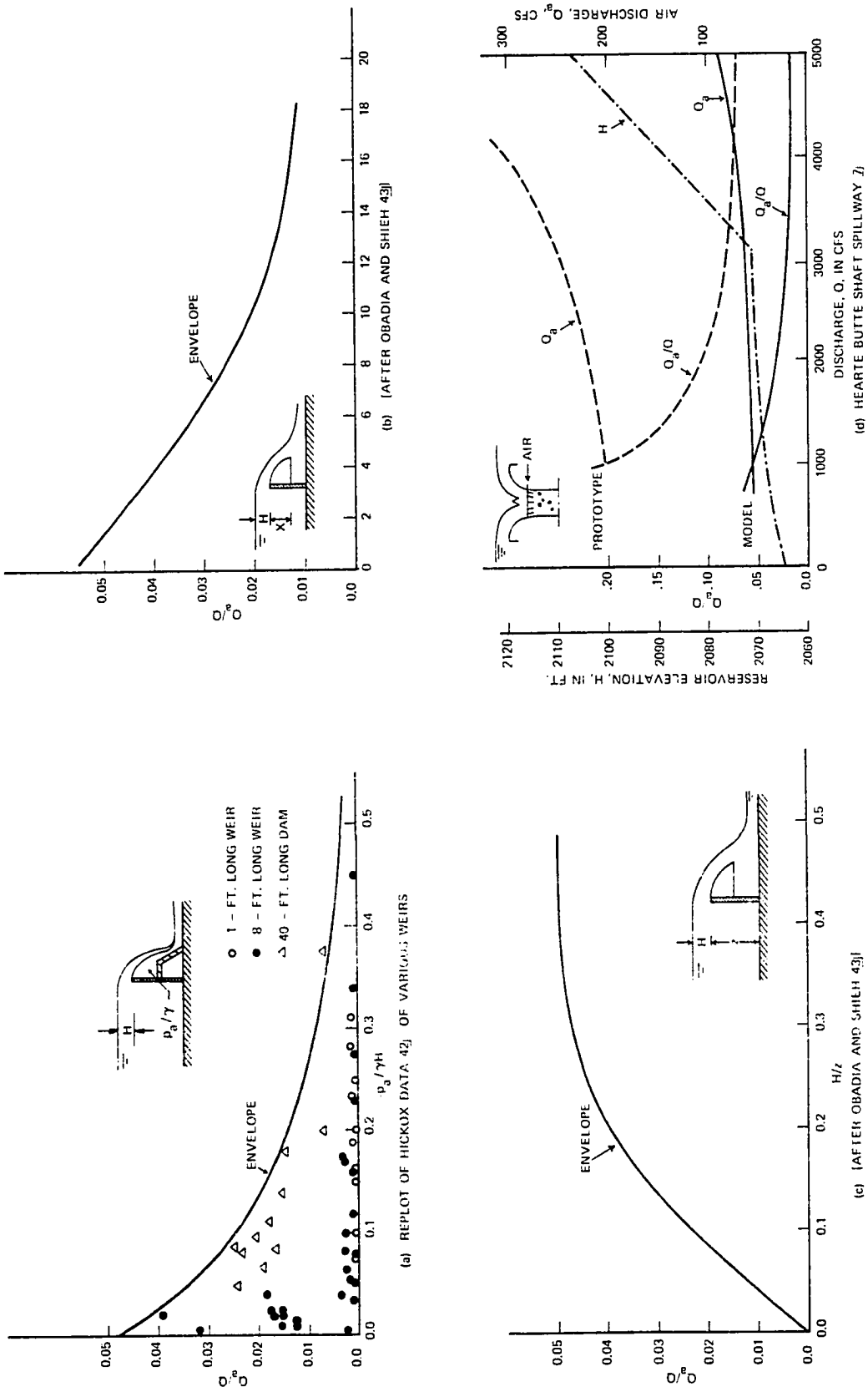

Figure 30. Air Demand of Flow over a Sharp-Crested Weir

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B. Transition from Short-Tube to Pipe Control

1. General

If the purpose of a dam is flood control, irrigation, or public or industrial water supply, where the discharge is to be limited in the river downstream from the dam, the shaft spillway is designed to operate unsubmerged at low discharges and to operate submerged at higher discharges. Submergence can be achieved by transition from weir to orifice control, as was discussed in Chapter III-A, or by transition from weir to short-tube control, as shown in Figures 5c and 6c. Of the ninety-six shaft spillways reviewed in Table A-3 of Appendix A, seventeen shaft spillways operated submerged at design capacity. Figure 31 shows the discharge curve of the Hearte Butte spillway in which the purpose of the dam was irrigation, flood control, and industrial water supply.

With short-tube control, the vertical shaft flows full of water and the flow control is at the bottom of the vertical shaft. Air entrainment from the pool surface ceases (Figure 29c) or is minimal if air is entrained through a vent at the throat (Figure 30d). The flow conditions in the horizontal conduit of either partly-full or pipe flow are influenced by the nature of the control at the bottom of the shaft. The discharge equation for short-tube control is:

$$Q = C_s A_s \sqrt{2gH_s} \tag{10}$$

in which C_s is a discharge coefficient, A_s is the cross-sectional area at the bottom of the vertical shaft, and H_s is the total head referenced to the bottom of the vertical shaft. The discharge equation for pipe control is:

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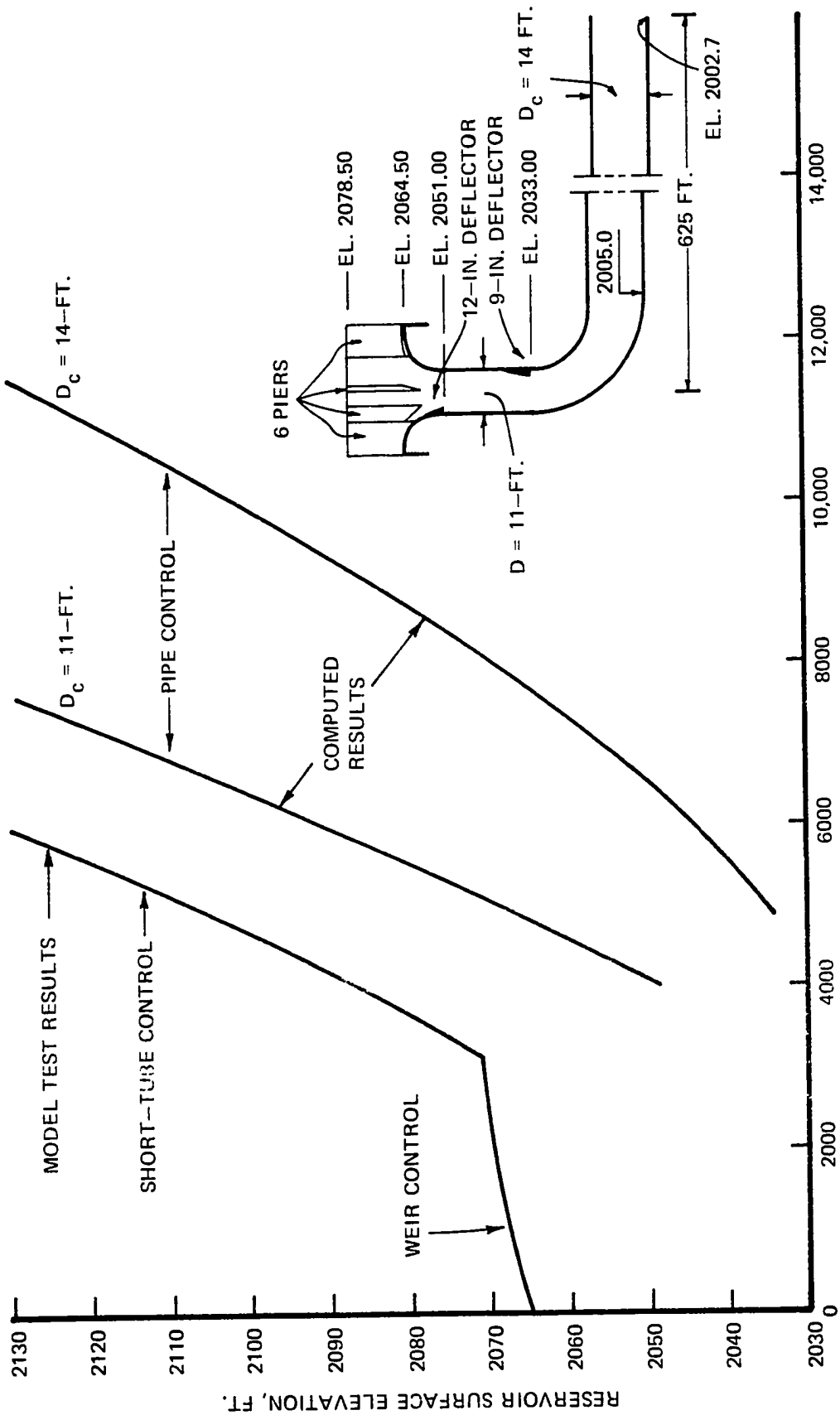

Figure 31. Reservoir Elevation - Discharge Relation of Hearte Butte Vertical-Shaft Spillway

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$$Q = A_c \sqrt{\frac{2gh_v}{K}} \qquad (11)$$

in which A_c is the cross-sectional area of the horizontal conduit, h_v is the velocity head, $V^2/2g$, at the outlet portal, and K is a total loss coefficient. The pool-discharge relationships for short-tube and pipe controls are shown in Figures 5e and 6e. The nature of the flow control at the bottom of the vertical shaft is affected by the bend geometry, by any inserts placed at the vertical bend such as a deflector, and by air entrainment.

Figure 32 shows a typical flow condition with short-tube control. Dimensionless parameters are used to evaluate the results. The dimensionless geometric variables are the ratio of the mean radius of curvature to the difference between the outer and the inner radii of the bend, r/B, and the ratio of the deflector thickness to the horizontal dimension of the vertical shaft, t/B. The dimensionless parameters of the flow in the horizontal conduit are the ratio of the air discharge to the water discharge, Q_a/Q, the Froude number, F, defined by $V/\sqrt{gd}$ in which V is the mean velocity and d is the mean depth of the water flow, and the ratio of the area of water flow to the area of the horizontal conduit, A/A_c. Froude number, the ratio of the water-flow area to the conduit area, and the ratio of the air discharge to the water discharge are determined throughout the water discharge range until incipient-sealing conditions.

2. Flow Conditions Prior to Sealing

Since any transition to pipe control occurs within the horizontal conduit and since sealing results from splashing and wave contact against

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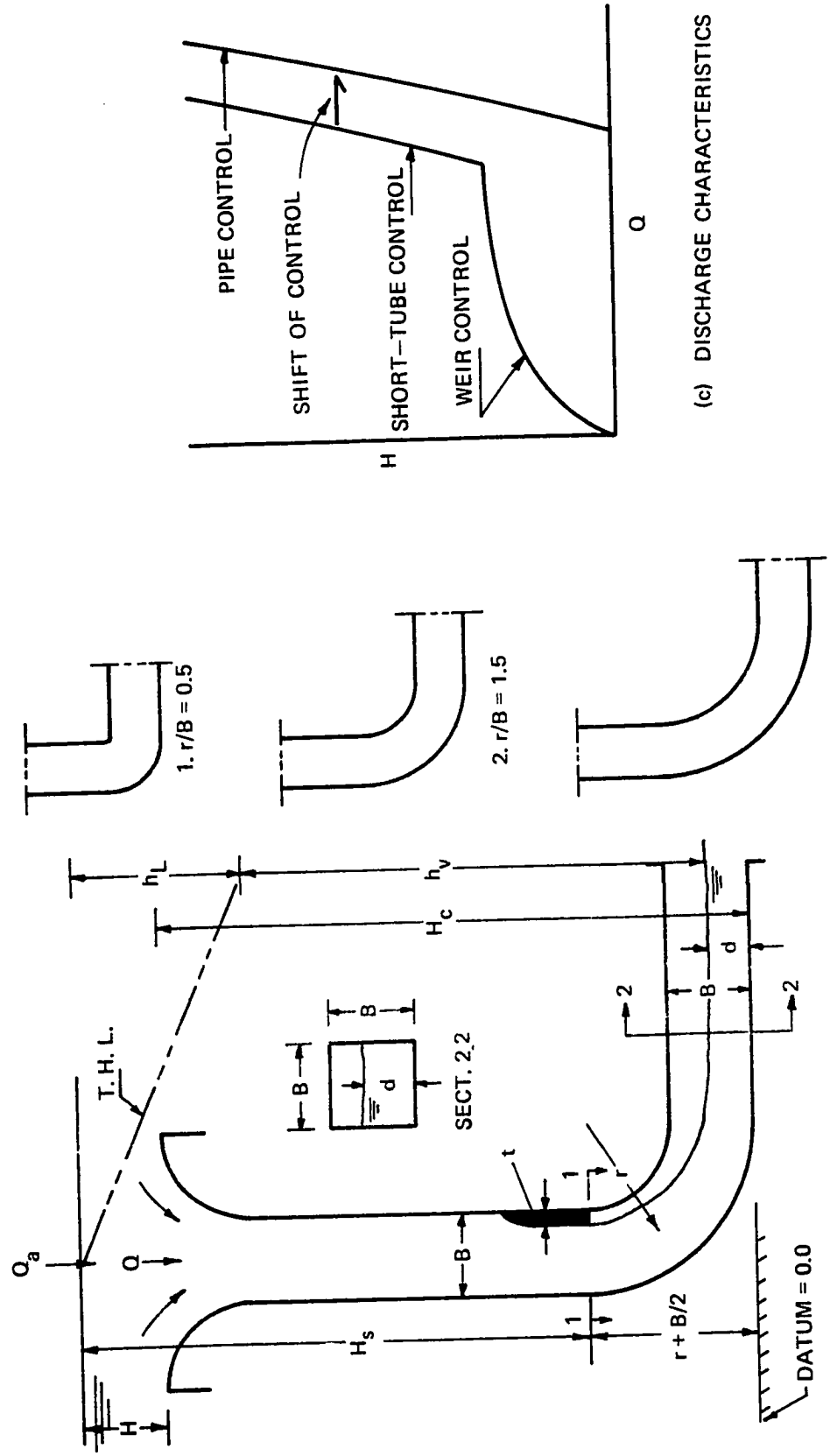

Figure 32. Definitive Sketch for Short-Tube Control Flow

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the roof, an analysis of the flow conditions within the horizontal conduit prior to sealing is required in order to evaluate the experimentally determined incipient-sealing conditions.

a. Theory. The following theoretical analysis is to evaluate the ratio of water-flow area to conduit area, A/A_c, as a function of the Froude number, F, for various bends and deflectors. In problems of this type, the value of A/A_c is expected to be a function of F for low values of the Froude number and to be independent of the Froude number for high values.

The value of A/A_c in the range of low Froude numbers can be derived by referring to Figure 32a. The continuity equation between sections 1 and 2 is

$$V_1 (B-t) = V_2 d \tag{12}$$

Assuming uniform velocity distribution at sections 1 and 2, assuming constant air pressure over the water surface, and neglecting head losses, the total-head equation is

$$\frac{V_1^2}{2g} + \left(r + \frac{B}{2}\right) = \frac{V_2^2}{2g} + d \tag{13}$$

Eliminating V_1, from Equation 13 by means of Equation 12 and solving for the Froude number, $F = V_2 / \sqrt{gD}$

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$$F = \sqrt{\frac{2\left(\frac{r/B + 1/2}{d/B}\right) - 2}{1 - \left(\frac{d/B}{1 - t/B}\right)^2}} \qquad (14)$$

Inasmuch as $d/B = A/A_c$, Equation 14 is the desired function relating A/A_c and F for the range of low Froude numbers.

The values of A/A_c in the range of high Froude numbers can be approximated from an irrotational-flow two-dimensional free-jet solution for a 90-degree miter bend obtained by Ambrose 80/. The flow depth in the horizontal conduit, d/B, depends on the vertical distance between the line of separation of the flow at the upstream end of the bend and the floor of the horizontal conduit, $r + \frac{B}{2}$, and on the horizontal dimension of the vertical shaft, B-t. Values of d/B from Ambrose's solution are tabulated below for values of r/B and t/B used in this experimental program.

$\frac{r}{B}$	$\frac{t}{B}$	$\frac{d}{B} = \frac{A}{A_c}$
0.5	0	0.52
	1/64	0.52
	1/16	0.52
	1/8	0.52
1.5	0	0.81
	1/64	0.81
	1/16	0.78
	1/8	0.75
2.5	0	0.94
	1/64	0.92
	1/16	0.89
	1/8	0.85

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b. Experimental Results. Experimental results and theoretical functions are shown in Figures 33-35 inclusive for flow conditions in the horizontal conduit. The solid lines in the figures are the theoretical functions of Equation 14 and of Ambrose. The theoretical functions are seen to be reasonable representations of the measured values except for the two bends, r/B = 1.5 and r/B = 2.5, without a deflector, t/B = 0, shown in Figures 34 and 35. The lack of agreement with the theoretical functions without a deflector is because in the theory leading to Equation 14 and in using Ambrose's solution, the line of separation was assumed to occur at the beginning of the bend as shown in Figure 36 whereas in the two exceptions the line of separation shifted to a lower elevation as shown in Figure 37.

Experimental results and theoretical functions are shown in Figures 38-43 inclusive for flow conditions within the horizontal conduit for various values of air concentration, Q_a/Q. The results with aerated flow are similar to those of non-aerated flow except for the two bends, r/B = 1.5 and r/B = 2.5, without a deflector, t/B = 0, shown in Figures 38 and 39. The lack of agreement is because the air separated from the water at the inner wall of the bend, due to the centrifugal force acting on the bubbly mixture, thus fixing the control at a section along the inner bend wall. Since the flow depth, d, was measured on the water manometer which determined the equivalent aerated-flow depth and since the mean velocity of aerated flow is larger than of a non-aerated flow 60/, the value of d and hence of A/A_c was smaller for aerated flow. The air bubbles passed through the bend and flowed into the horizontal conduit in an ascending trajectory (Figure 44) creating

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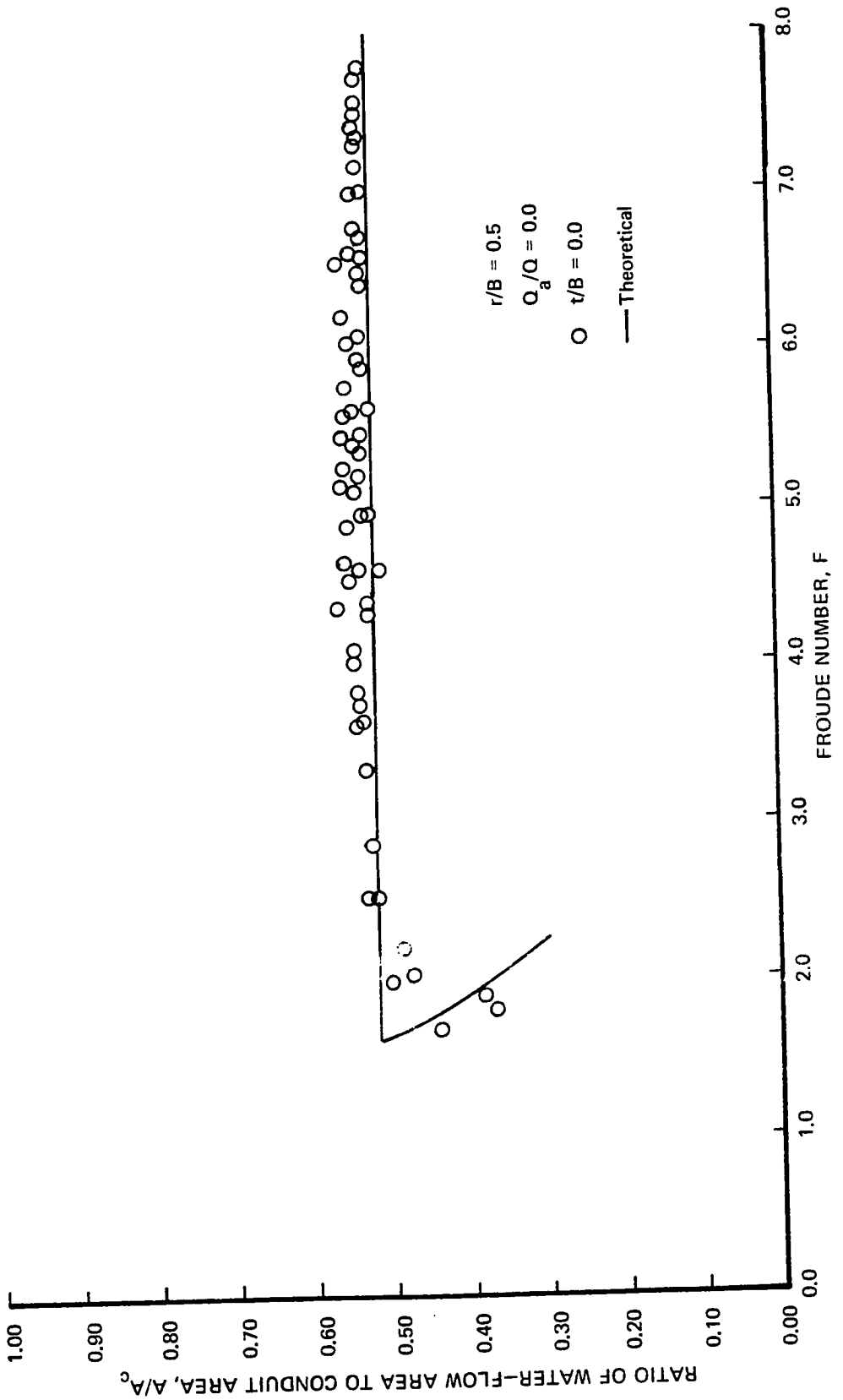

Figure 33. Percent Flow Area Versus Froude Number Prior to Sealing (Short-Tube Control, and r/B = 0.5)

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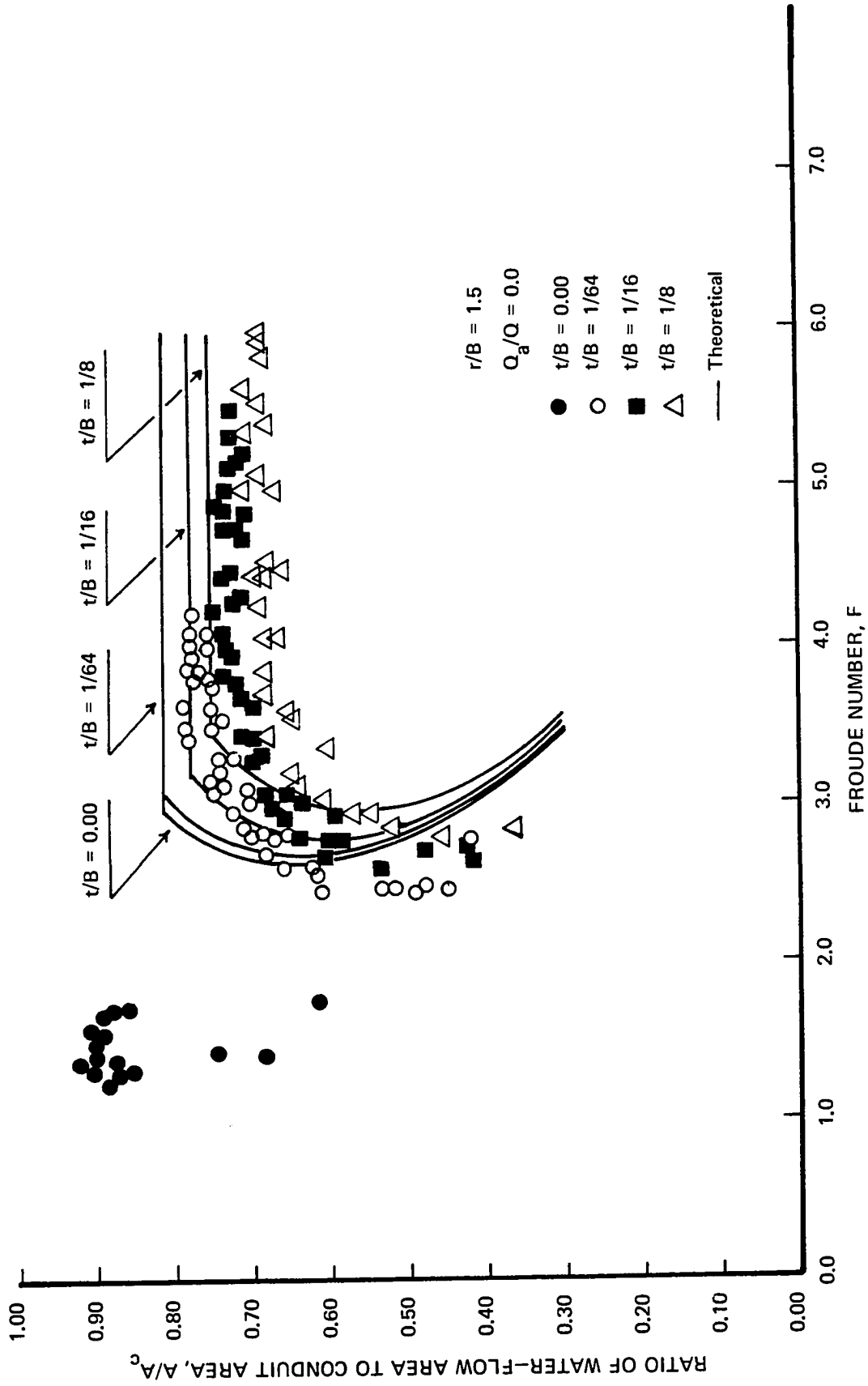

Figure 34. Percent Flow Area Versus Froude Number Prior to Sealing (Short-Tube Control, and r/B = 1.5)

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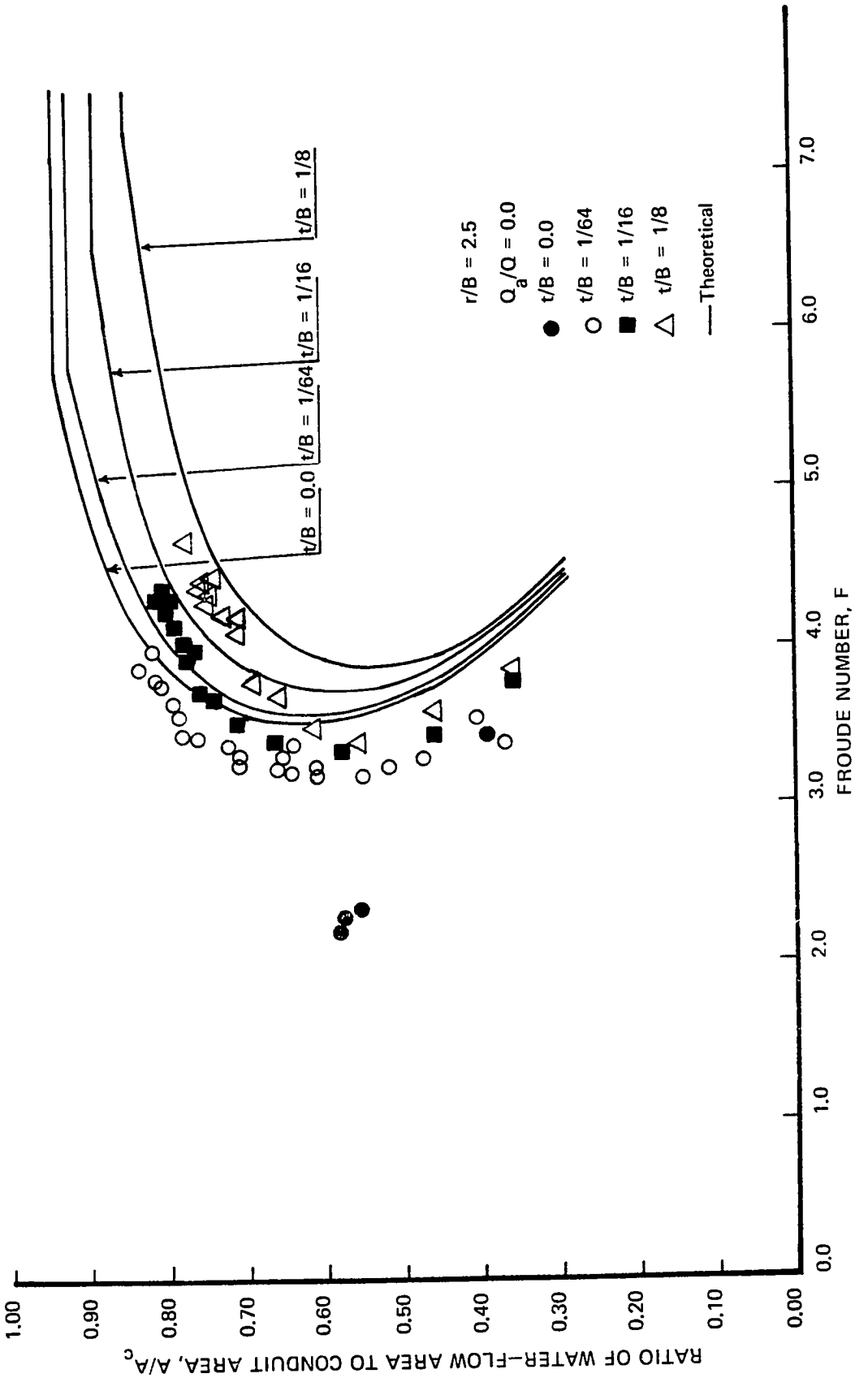

Figure 35. Percent Flow Area Versus Froude Number Prior to Sealing (Short-Tube Control, and r/B = 2.5)

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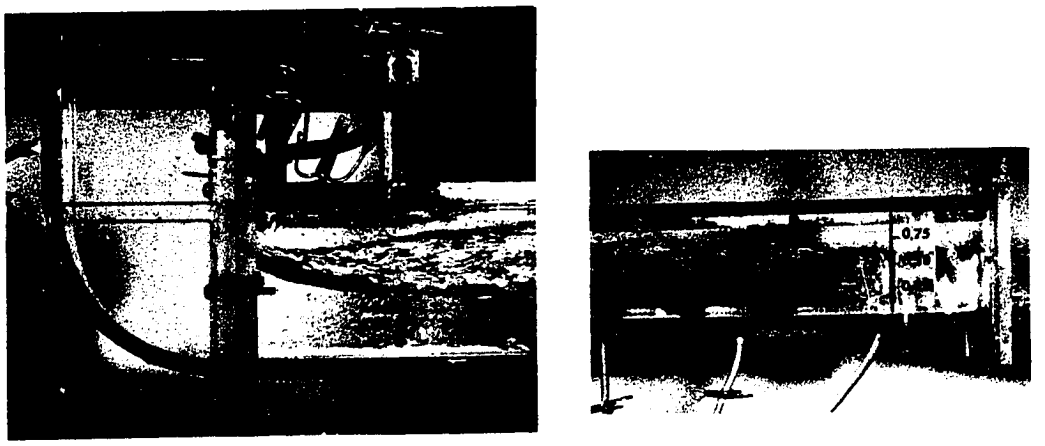
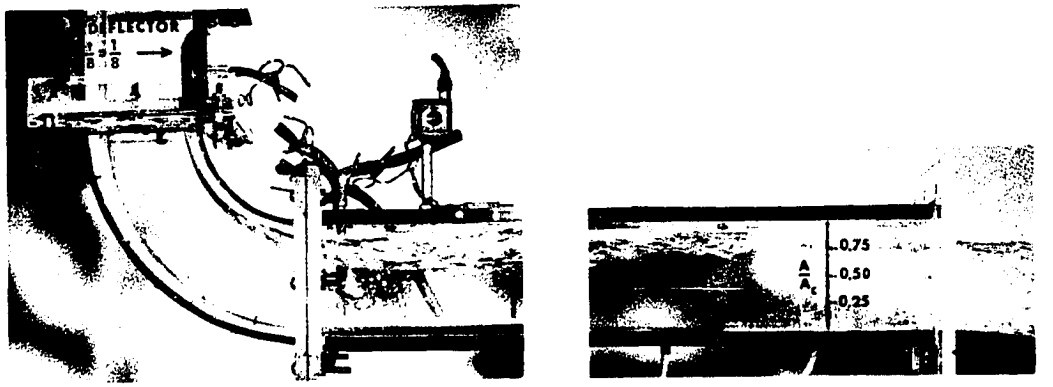
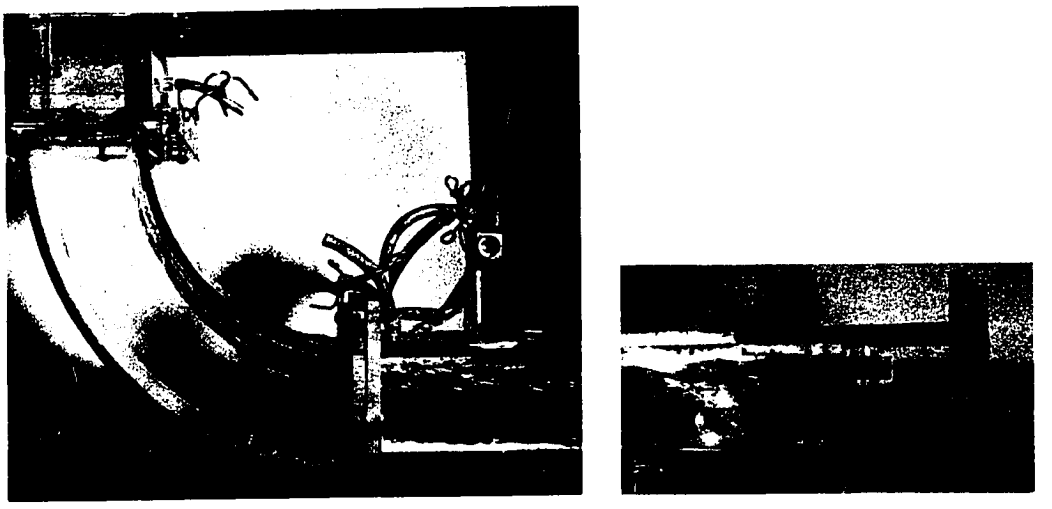


(a) r/B = 0.5 and t/B = 0.0



(b) r/B = 1.5 and t/B = 1/8



(c) r/B = 2.5 and t/B = 1/8

Figure 36. Flow Conditions Downstream of the Deflector, t/B = 1/8, at the Crown of the Bend at Incipient Sealing (Short-Tube Control, and $Q_a/Q = 0.0$)

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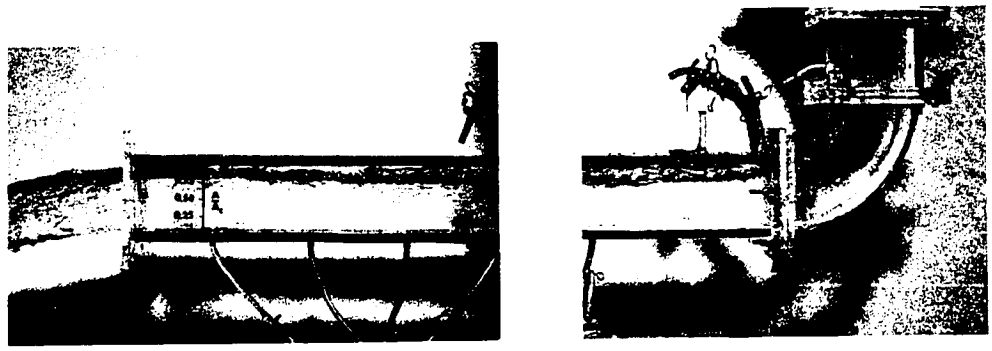
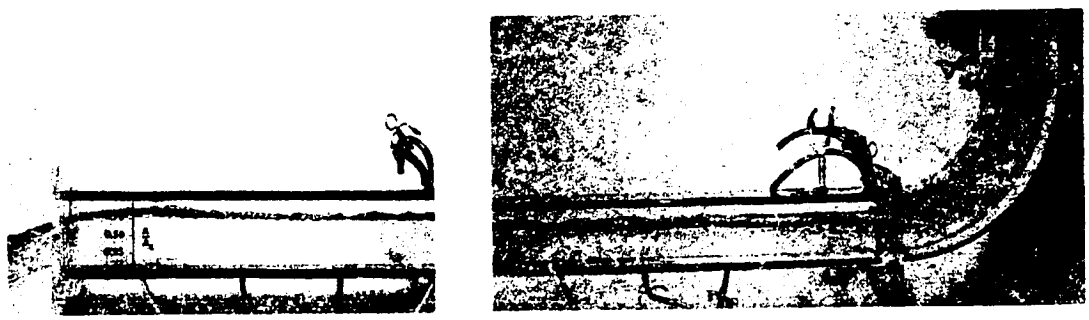


(a) r/B = 1.5 and t/B = 0.0



(b) r/B = 2.5 and t/B = 0.0

Figure 37. Flow Conditions at the Bend and in the Horizontal Conduit at Incipient Sealing (Short-Tube Control, Q_a/Q = 0.0, and t/B = 0.0)

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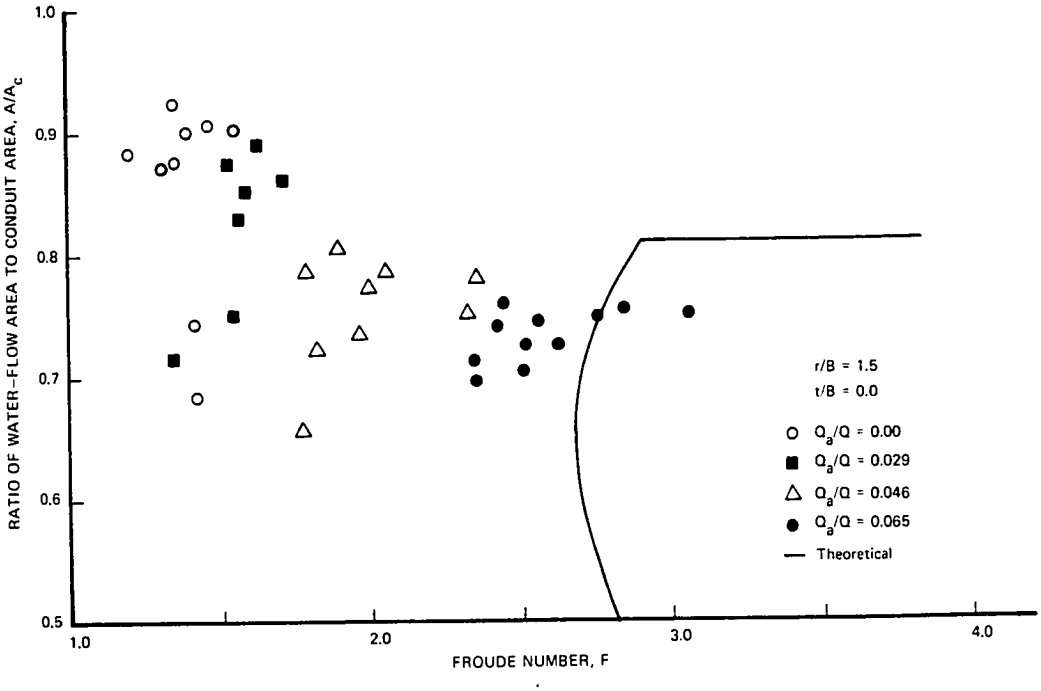

Figure 38. Percent Flow Area Versus Froude Number Prior to Sealing (Short-Tube Control, Aerated Flow, r/B = 1.5, and t/B = 0.0)

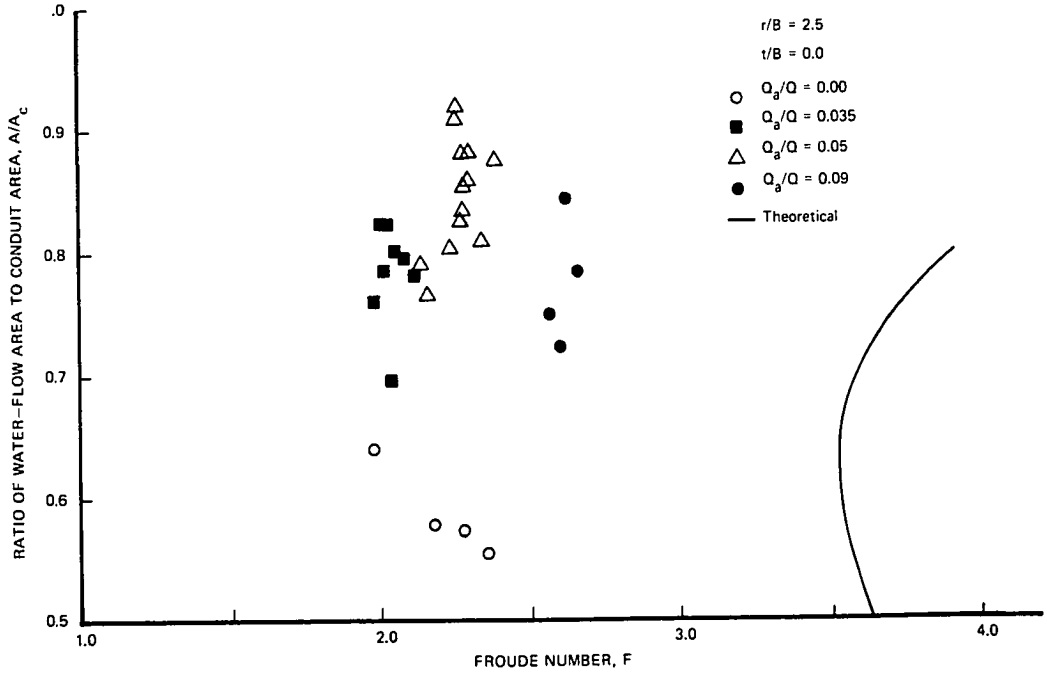

Figure 39. Percent Flow Area Versus Froude Number Prior to Sealing (Short-Tube Control, Aerated Flow, r/B = 2.5, and t/B = 0.0)

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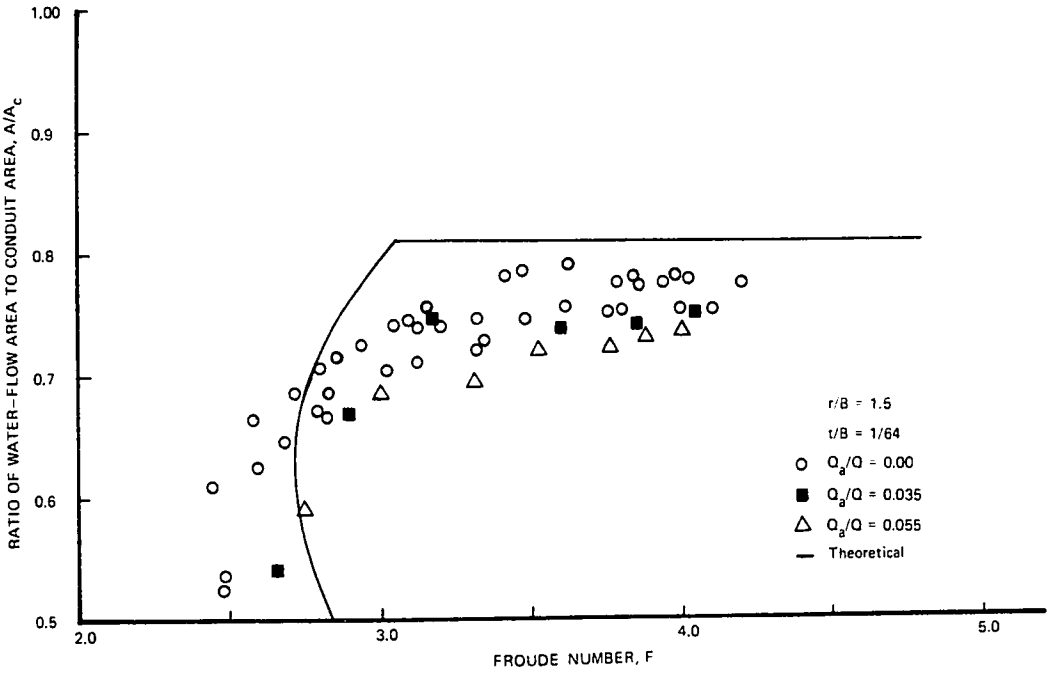

Figure 40. Percent Flow Area Versus Froude Number Prior to Sealing (Short-Tube Control, Aerated Flow, r/B = 1.5, and t/B = 1/64)

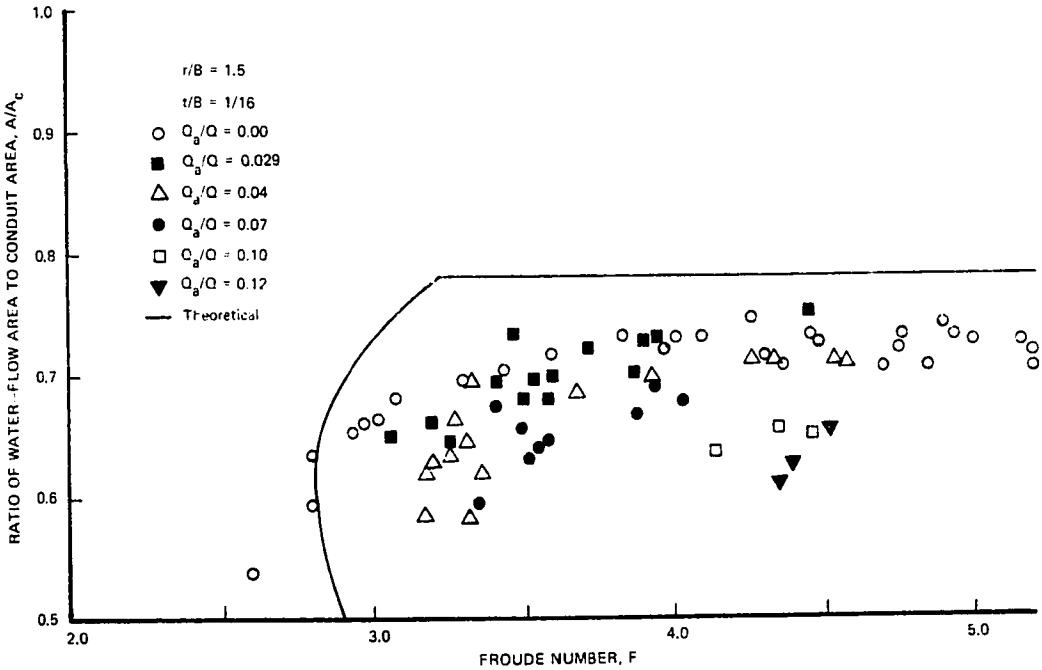

Figure 41. Percent Flow Area Versus Froude Number Prior to Sealing (Short-Tube Control, Aerated Flow, r/B = 1.5, and t/B = 1/16)

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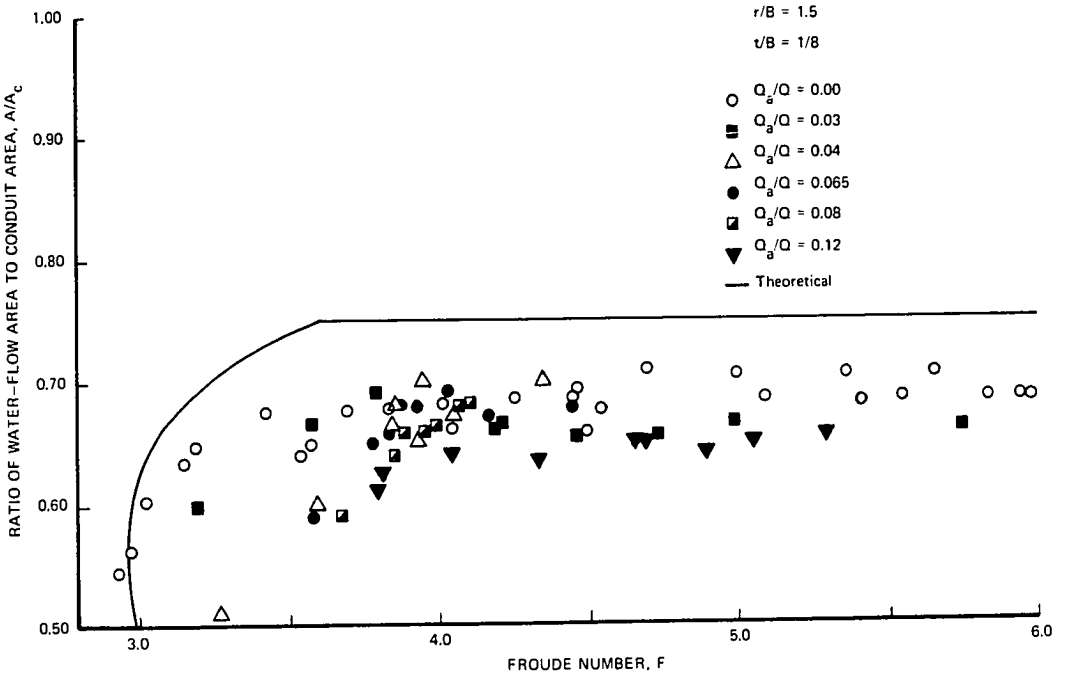

Figure 42. Percent Flow Area Versus Froude Number Prior to Sealing (Short-Tube Control, Aerated Flow, r/B = 1.5, and t/B = 1/8)

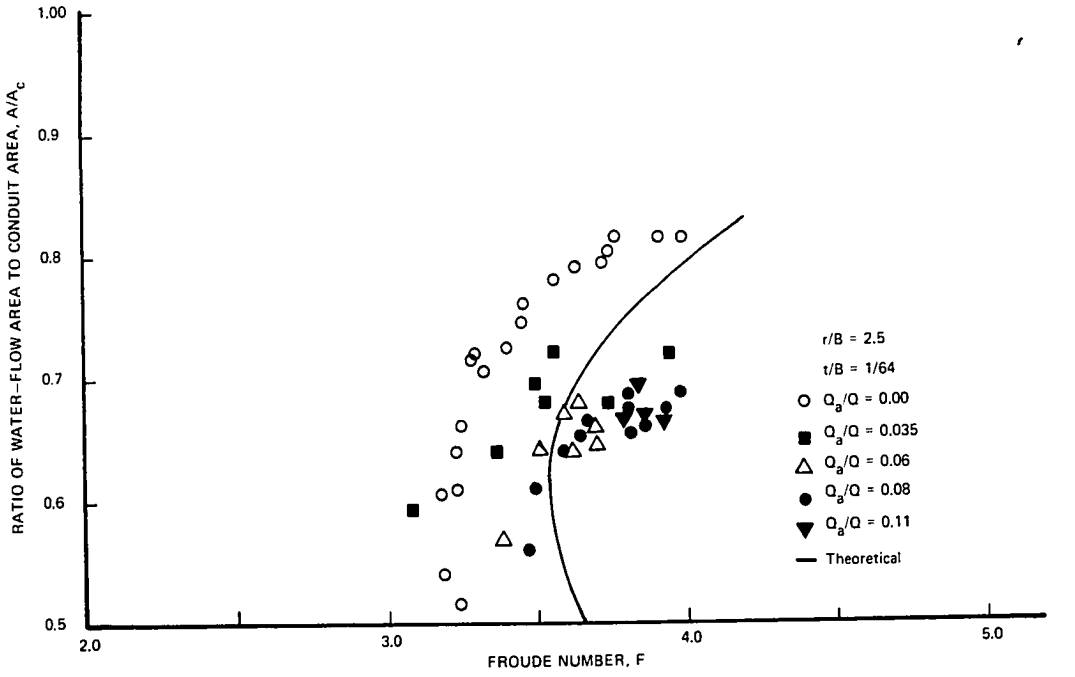

Figure 43. Percent Flow Area Versus Froude Number Prior to Sealing (Short-Tube Control, Aerated Flow, r/B = 2.5, and t/B = 1/64)

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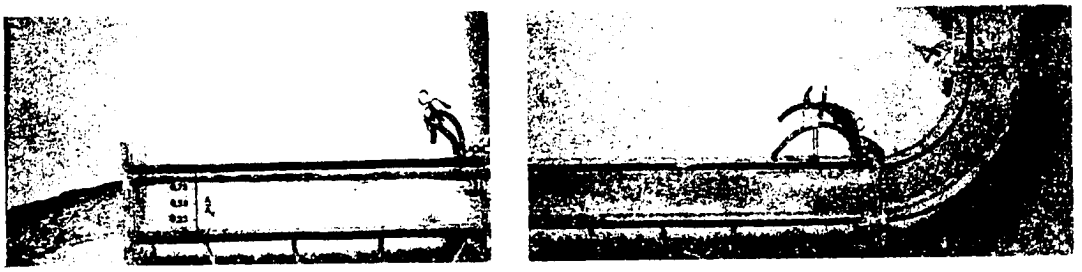
(a) r/B = 1.5 and t/B = 0.0



(b) r/B = 2.5 and t/B = 0.0

Figure 44. Flow Conditions at the Bend and in the Horizontal Conduit at Incipient Sealing (Short-Tube Control, Q_a/Q = 0.12, and t/B = 0.0)

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a frothy surface as the bubbles escaped from the water surface. Water droplets splashed against the roof and the maximum water depth (or spray) was more than the corresponding non-aerated flow.

3. Flow Conditions at Incipient Sealing

Conditions at incipient sealing are the upper limit for the flow in the horizontal conduit before a shift from short-tube to pipe control occurs. Figures 36, 37, 44, and 45 show the flow conditions in the horizontal conduit at incipient sealing. Figure 46 shows typical piezometric-head lines along the conduit.

Before discussing the flow conditions at incipient sealing that eventually lead to sealing of the conduit, the phenomena that could not have caused sealing are reviewed.

The first possibility is the hydraulic jump. A hydraulic jump can occur in a rectangular conduit if there exists a subcritical conjugate depth, d_2, downstream of the supercritical flow of depth d_1, that satisfies the equation

$$\frac{d_2}{d_1} = \frac{1}{2}\left(\sqrt{1 + 8F_1^2} - 1\right) \qquad (15)$$

For the bend of r/B = 0.5 sealing occured at a Froude number F = 8.0 (Figure 33) which requires a conjugate depth, d_2, equal to 11 d_1. A conjugate depth, d_2, was not available since the flow discharged freely at the outlet.

The second possibility is that the backwater curve depth increases. For supercritical flows (F > 1) on mild slopes the backwater curve is classified M-3. Backwater profile computations, with the point

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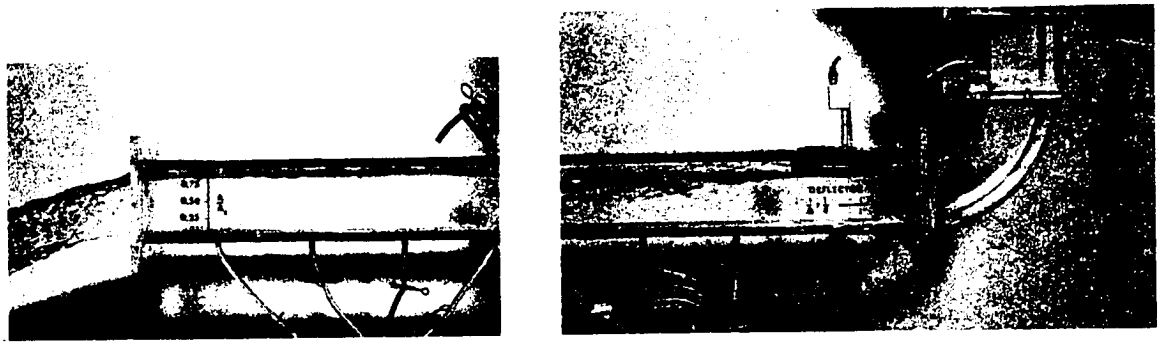

(a) r/B = 1.5 and t/B = 1/4

Figire 45. Flow Conditions Downstream of the Deflector, t/B = 1/4, at the roof of the Conduit at Incipient Sealing (Short-Tube Control, and Q_a/Q = 0.9)

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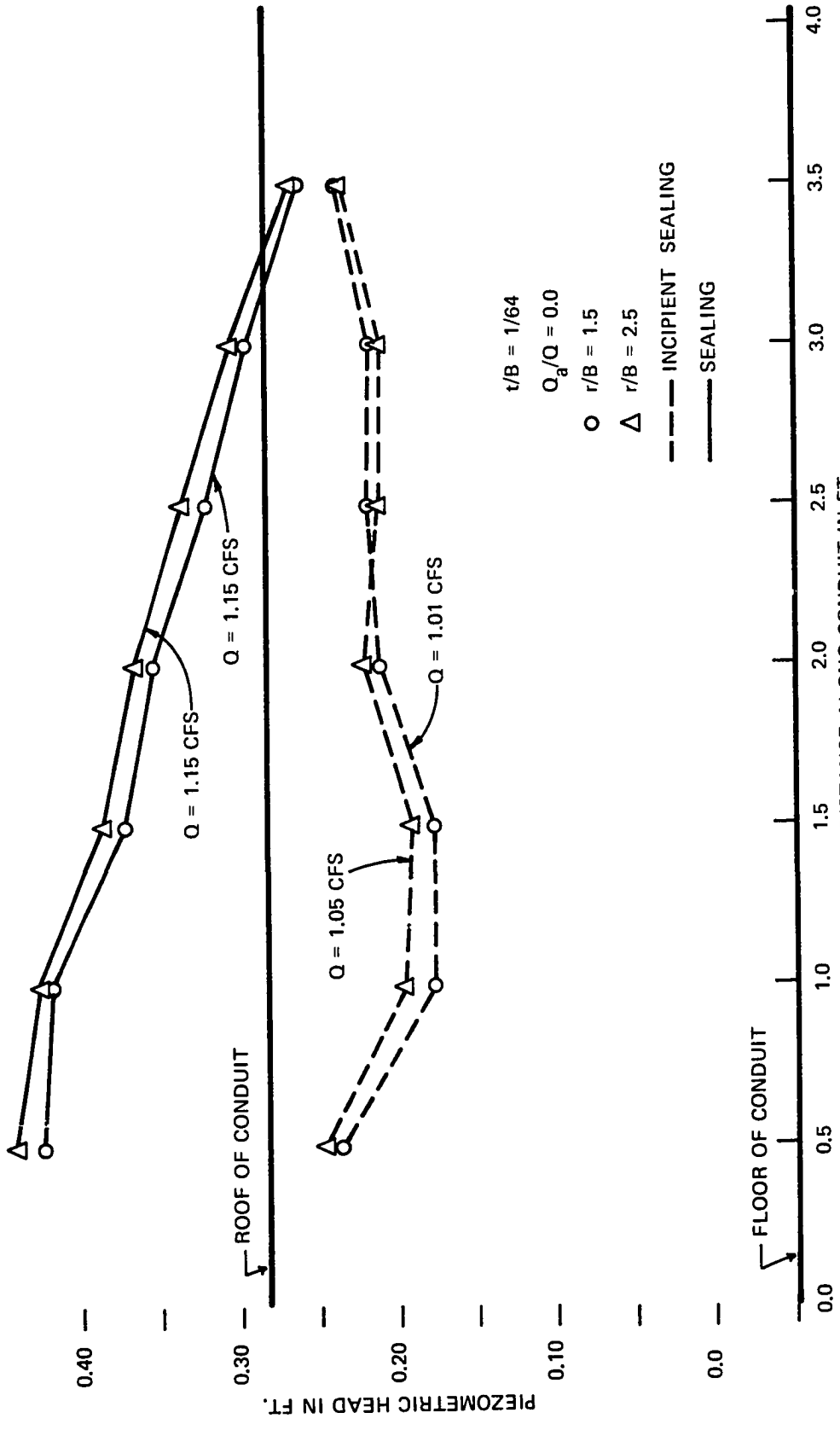

Figure 46. Typical Piezometric-Head Elevations Along Horizontal Conduit (Short-Tube Control)

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of separation fixed at the deflector at the crown of the bend, show that the flow depth at the outlet portal decreases as the discharge increases. Sealing, therefore, due to a backwater profile touching the roof of the conduit was not possible.

An explanation of the flow conditions leading to and at incipient sealing follows. As the water discharge was increased, the free-surface-supercritical flow, due to the shear stress developed at the interface between the water and the air, dragged out the layer of air adjacent to the water surface as shown in Figure 47a. The interfacial shear stress depends on the relative velocity of the water and air flow and on the interfacial disturbances 81, 82, 83/. The interfacial disturbances are due to the nature of the supercritical flow and are due to the water droplets breaking away from the water surface. Vedernikov 84/ and Rouse 85/ found that the water surface in supercritical flow is unstable and wavy. Clumps and droplets of water break away from the water surface when the transverse velocity of water and the turbulence are sufficiently strong at the interface or when the air bubbles in an aerated flow escape from the water surface forming a froth. Figures 36,37,44, and 45 show the water droplets over the turbulent water-air interface. From the equation of continuity, an equal amount of air has to enter from the outlet portal to replenish the amount of the outflowing air. A circulatory air current was thus established as shown in Figure 47a. Sketches of the velocity distribution and the shear stress distribution in the air layer are shown in Figure 47b. The drag of the water on the air established a negative pressure gradient inside the conduit. The pressure results are shown in Figure 48. The pressure decreased with

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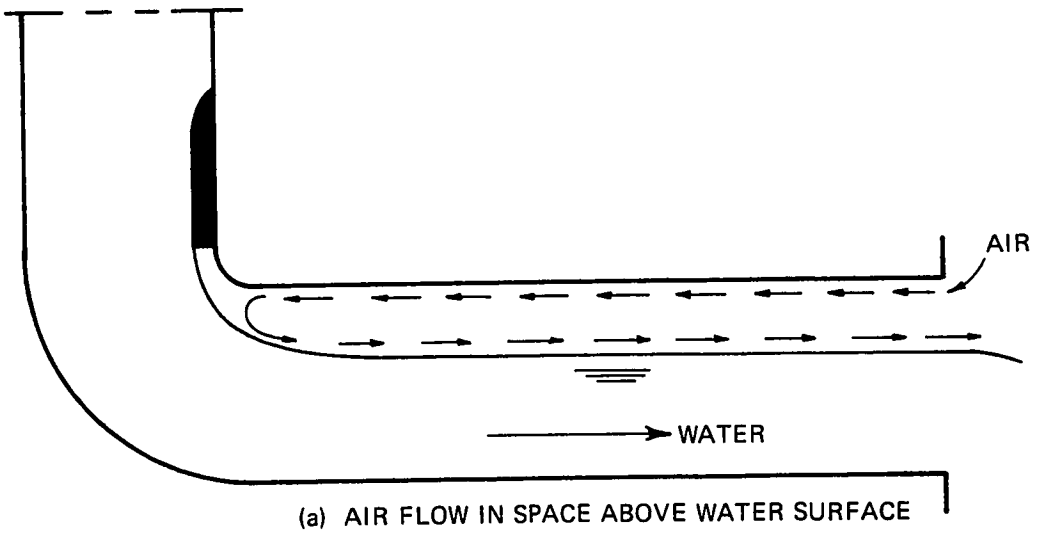

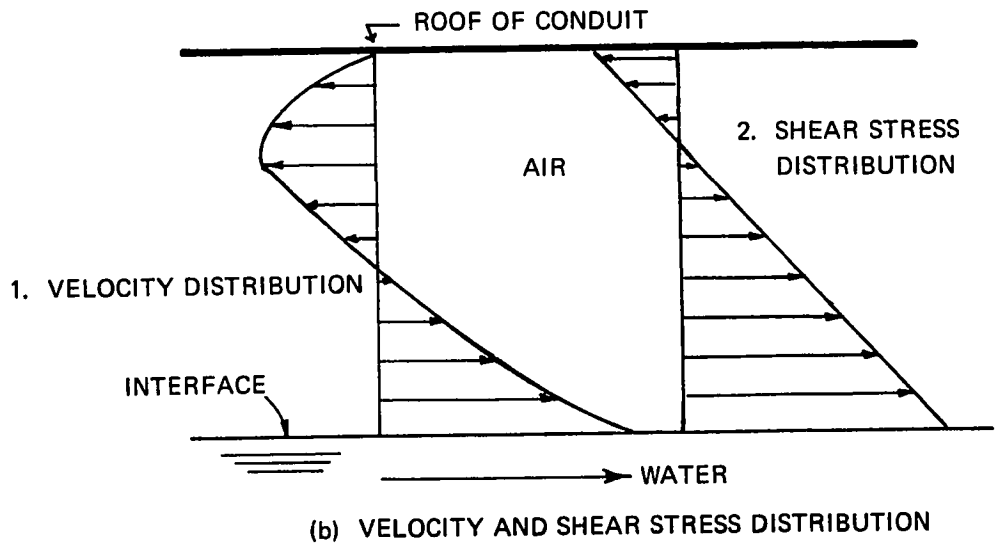

Figure 47. The Circulatory Air Current in the Conduit

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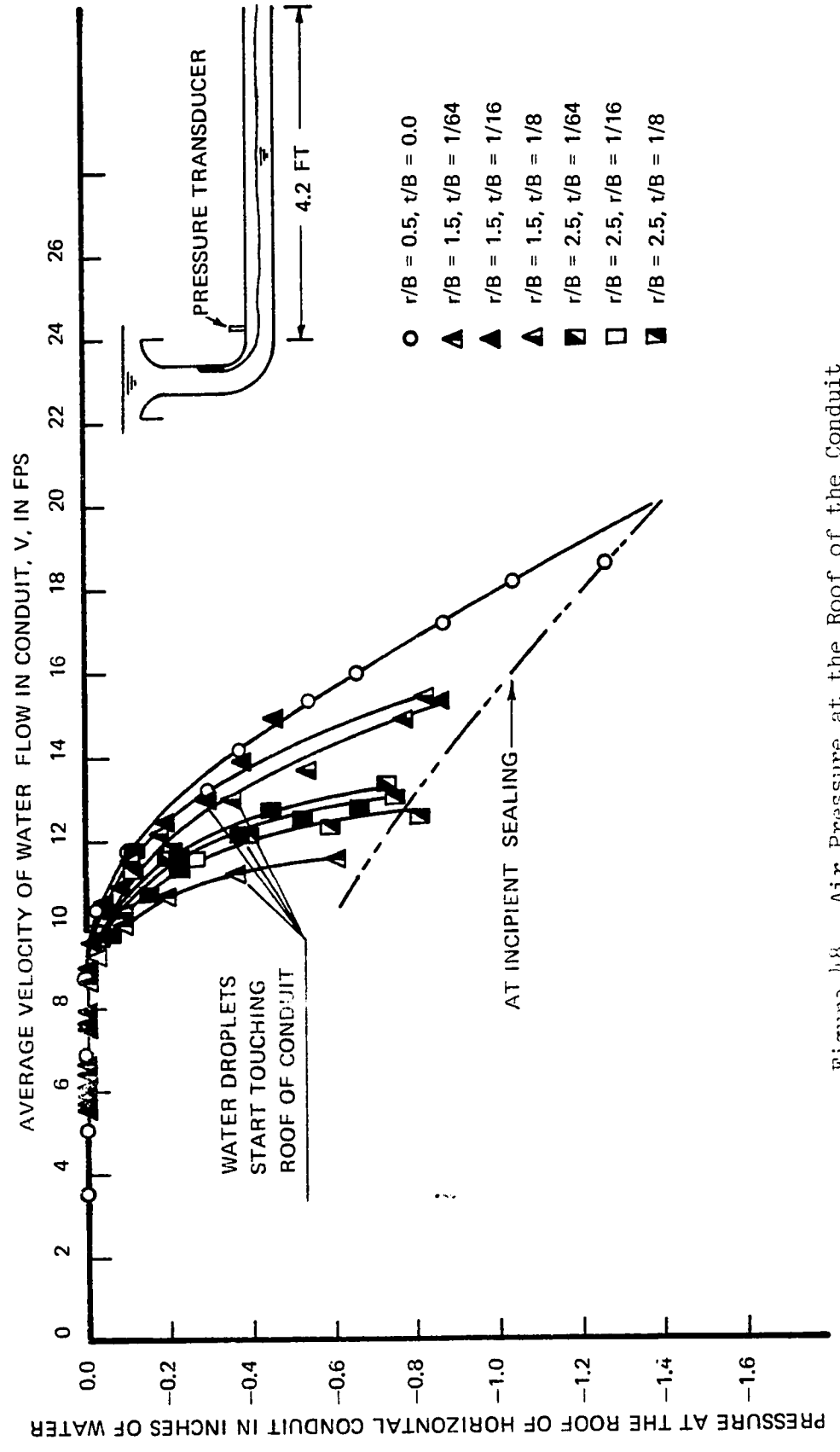

Figure 18. Air Pressure at the Roof of the Conduit

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the increase of the water velocity and of the interfacial disturbances. The velocity of the inflowing air depends on the interfacial shear stress and on the area of the air flow. With the increase of the water velocity and/or aeration of the flow, water droplets splashed at the roof of the conduit, more air was dragged out, the area of the inflowing air flow became smaller, and subsequently the velocity of the inflowing air increased. If the velocity of the water droplets in the direction of the water flow is greater than the velocity of the inflowing air, the water droplets fall back to the water surface without choking the conduit as shown in Figure 49a. At incipient sealing, the velocity of the inflowing air becomes larger than the velocity of the droplets, hence the water droplets deflect into the direction of the inflowing air as shown in Figure 49b. The water droplets choke the air layer above the water surface and thus seal the conduit. Appendix B-1 shows computations of the inflowing air velocity, based on the pressure at the roof of the conduit, as compared to the water velocity at incipient sealing. Qualitative runs were made with the air vents open at the upstream end of the conduit. Incipient sealing was delayed since the air entering the conduit from the vents substituted for the need of the inflow of air from the outlet portal, thus the air velocity profile changed to flow in the same direction as the water flow as shown in Figure 49c. With aerated flow, the increased spray caused a decrease of the space area and an increase of the velocity of the inflowing air which eventually hastened sealing.

Figure 50 shows the relation between the ratio of water-flow area to conduit area and the Froude number for all the bends and deflectors

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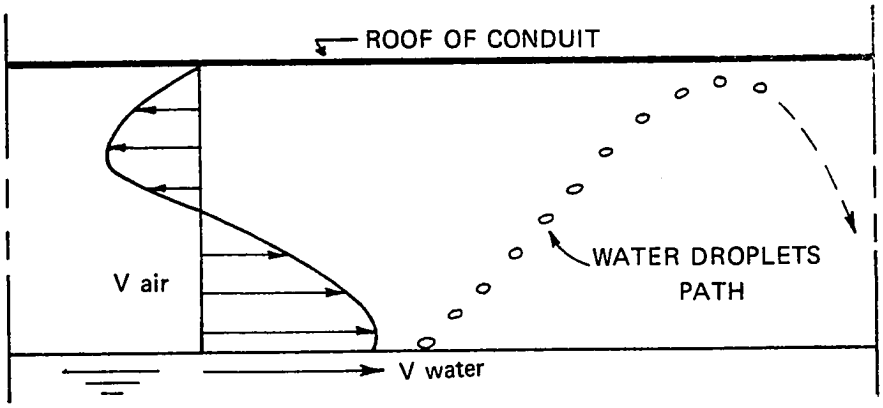
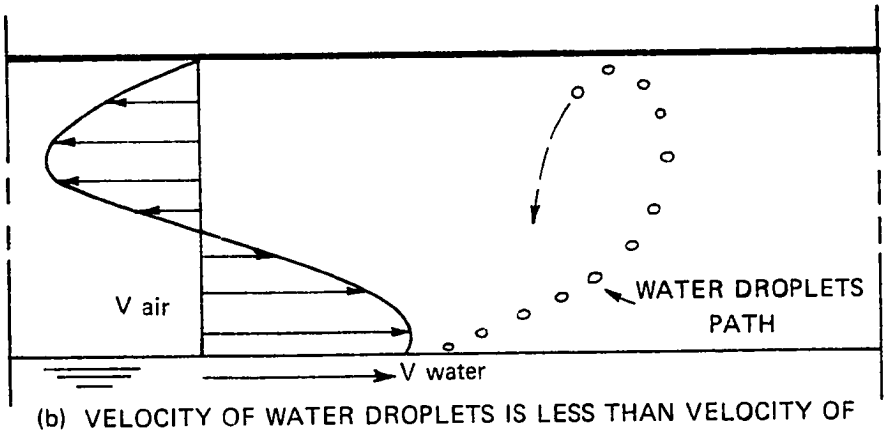
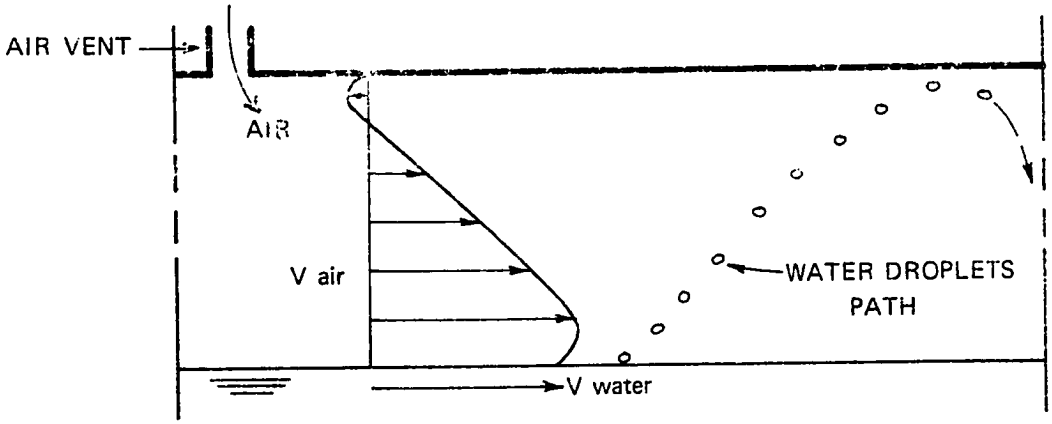


(a) VELOCITY OF WATER DROPLETS IS LESS THAN VELOCITY OF INFLOWING AIR



(b) VELOCITY OF WATER DROPLETS IS LESS THAN VELOCITY OF INFLOWING AIR



(c) AIR VENT AT UPSTREAM END OF CONDUIT

Figure 49. Water Droplets Path for Various Air Velocity Distributions

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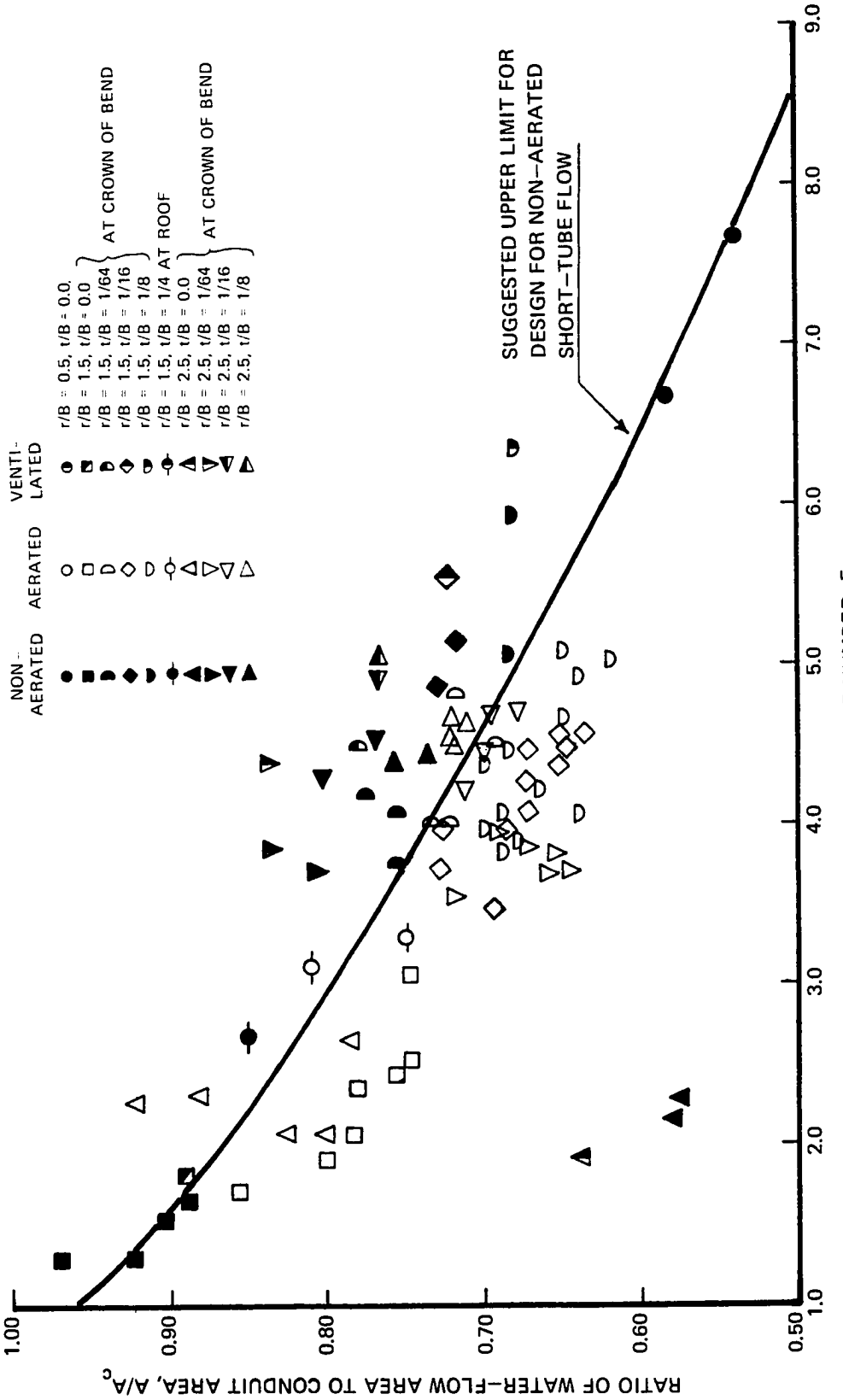

Figure 50. Percent Flow Area Versus Froude Number at Incipient Sealing (Short-Tube Control)

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tested at incipient sealing. The ordinates for the bend of r/B = 2.5, with t/B = 0.0, were low because the control shifted quickly to the downstream end of the bend and a closer measurement to incipient sealing could not be made. The ordinates for the bends r/B = 1.5 and 2.5 with deflectors show some scatter which was due to an increased disturbance at the edge of the deflector or at the joints of the model. At higher Froude numbers more air space above the water surface is needed to accommodate the splash of the water droplets and to provide air-flow area large enough to keep the velocity of the inflowing air less than the velocity of the water droplets. With some aeration the water splash increased and incipient sealing was at lower Froude numbers than the corresponding non-aerated flow. With additional ventilation from the air vents at the roof of the conduit, incipient sealing was at higher Froude numbers than the corresponding non-ventilated flow.

C. Transition From Weir to Pipe Control

1. General

If the purpose of the shaft spillway is to pass the excess flood water without overtopping the dam, the spillway is designed to discharge freely with weir control throughout the discharge range as shown in Figure 5a. Of the ninety-six shaft spillways reviewed in Table A-3 of Appendix A, thirty-one shaft spillways are known to have operated with weir control at design capacity.

With weir control, an air-water mixture flows in the vertical shaft and in the horizontal conduit. The discharge equation for weir control is:

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$$Q = C\, D_{cr}\, g^{0.5} H^{1.5} \tag{8}$$

in which C is a discharge coefficient, D_{cr} is the diameter at the inlet crest, and H is the total head over the inlet crest. The discharge equation for pipe control is:

$$Q = A_c \sqrt{\frac{2gh_v}{K}} \tag{11}$$

A typical discharge-rating curve, that of Davis Bridge shaft spillway, is shown in Figure 51.

Air is entrained freely from the atmosphere at the pool surface. Figure 29 shows the variation of air concentration into the water flow throughout the weir control range as were measured in models. The air concentrations ranged from 100 per cent at low discharges to zero per cent at the transition to orifice control.

This experimental investigation was to study systematically the effect of air concentration, Q_a/Q, bend curvature, r/B, and the ratio of the deflector thickness to the horizontal dimension of the shaft, t/B, on sealing of the horizontal conduit. Weir control conditions were simulated by letting the water flow eject from a multiple-tube outlet (Figure 14) into the vertical shaft and then through the horizontal conduit. Various amounts of air were entrained into the water flow, at a section just below the multiple-tube outlet, to produce the air-water mixture. Sealing of the conduit is defined by the condition when any section of the conduit is under pressure. Sealing was determined by taking piezometric-head measurements along the floor of the conduit and by pressure measurements at the roof of the conduit. Dimension-

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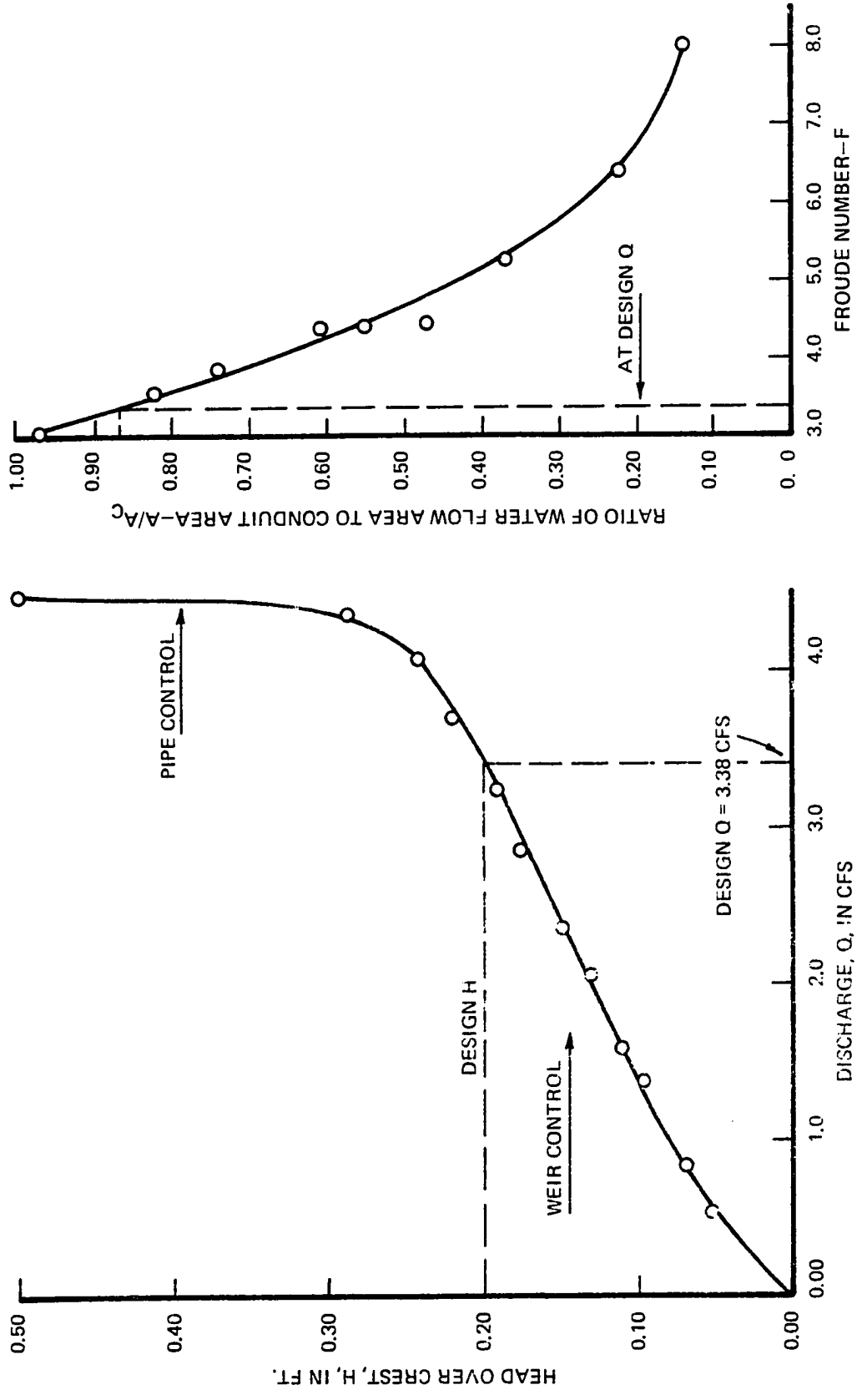

Figure 51. Discharge Rating Curve and Flow Characteristics in Conduit for Davis Bridge Vertical-Shaft Spillway

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less parameters are used to describe the characteristics of the flow in the horizontal conduit. The dimensionless variables are the bend curvature, r/B, and the ratio of the deflector thickness to the horizontal dimension of the shaft, t/B. The dimensionless parameter of the flow in the horizontal conduit are the ratio of the air discharge to the water discharge, Q_a/Q, the Froude number, F, and the ratio of the area of the water flow to the area of the conduit, A/A_c. Froude number, the ratio of the area of the water flow to the area of the conduit, and the ratio of the air discharge to the water discharge were determined throughout the discharge range until incipient sealing.

2. Flow Conditions Prior to Sealing

Since transition to pipe control occurs within the horizontal conduit and since sealing results from wave contact against the roof, an analysis of the flow conditions within the horizontal conduit prior to sealing is required in order to evaluate the experimentally determined incipient-sealing conditions.

a. Theory. The wave height in the free-surface flow in the horizontal conduit depends on the Froude number. Considering a vertical shaft spillway with a total head, H_T, from the pool surface to the flow surface in the conduit and assuming the head losses, h_L, to be approximately equal to 15 per cent of the total head, then the velocity of the flow in the conduit can be written as

$$V = \sqrt{2g\ (H_T - h_L)} \tag{16}$$

Froude number can be related to the ratio of water-flow area to conduit area, A/A_c, as

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$$F = \frac{V}{\sqrt{g \frac{d}{D_c} D_c}} = \sqrt{\frac{2}{d/D_c} \frac{H_T - h_L}{D_c}} \qquad (17)$$

in which d is the flow depth in the conduit and D_c is the conduit diameter. Inasmuch as A/A_c is related to d/D_c, Figure 52 shows the relation between F and A/A_c according to Equation 17 for the maximum and minimum H_T of existing spillways. Experimental results from model tests of existing shaft spillways are also shown in Figure 52.

b. Experimental Results. The experimental results are shown in Figures 53-57, inclusive for flow conditions in the horizontal conduit. The experimental results are in close agreement with Equation 17 and the existing shaft spillways. The variation of the air concentration throughout the discharge range is also comparable to actual conditions where air is entrained from the pool surface (Figure 29). The surface of the air-water mixture flow in the horizontal conduit was wavy and frothy as shown in Figure 58. The wavy flow surface in the horizontal conduit is caused by the impact of the falling air-water mixture on the floor of the conduit. The bend of r/B = 0.5 induced the largest waves and the bend of r/B = 2.5 induced the smallest waves. Air bubbles ejecting from the water surface formed a frothy surface with a layer of water droplets over the main mass of water flow. With more air entrainment into the water flow, the spray of droplets and the layer of froth increased, the amount of air ejecting as the bubbles of air escaped through the water surface increased, and the layer of froth moved with the direction of the water flow as shown in Figure 59. As

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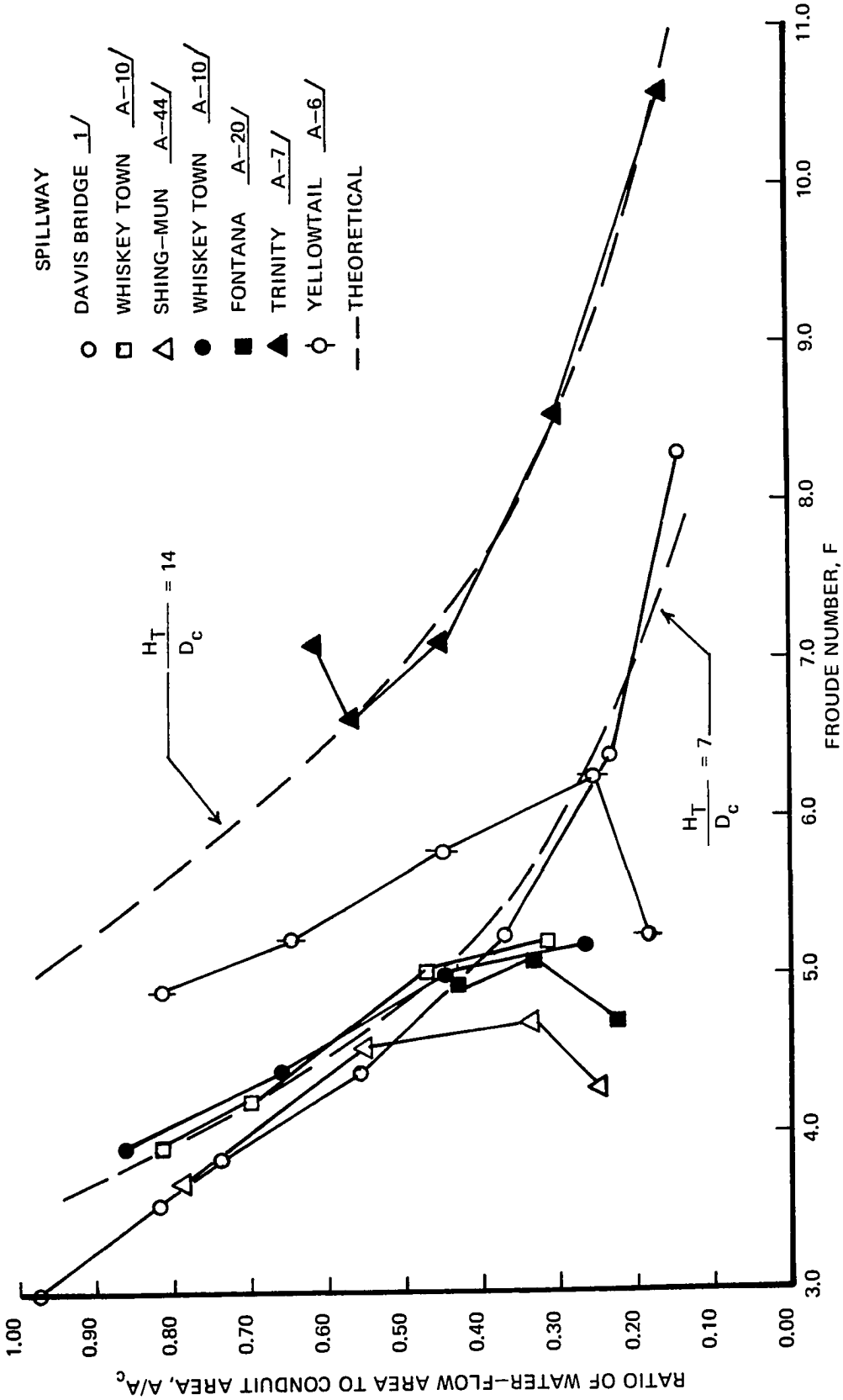

Figure 52. Percent Flow Area Versus Froude Number Prior to Sealing for Existing Shaft Spillways (Weir Control)

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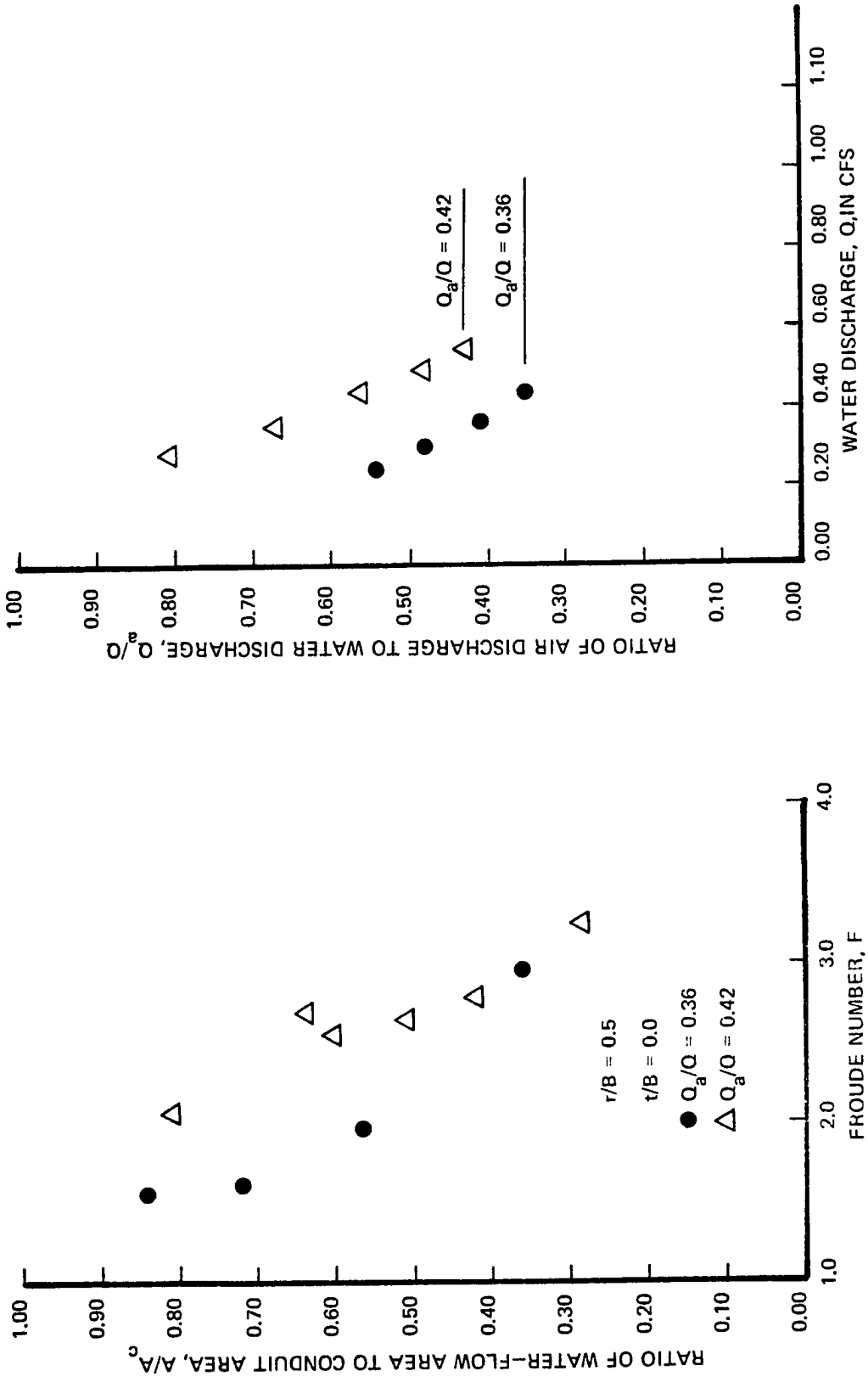

Figure 53. Percent Flow Area Versus Froude Number with the Corresponding Air Concentrations Prior to Sealing (Weir Control, r/B = 0.5, and t/B = 0.0)

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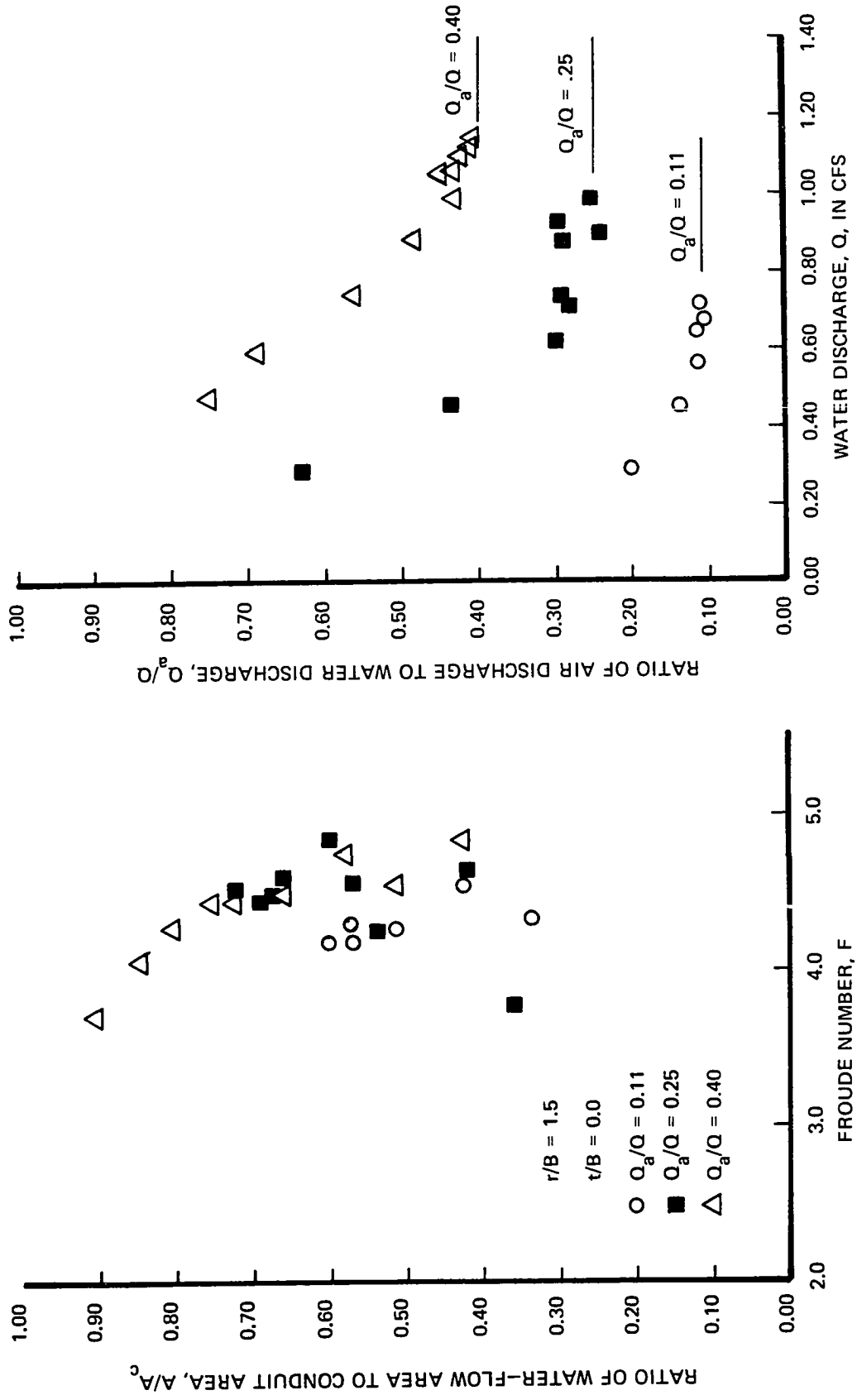

Figure 54. Percent Flow Area Versus Froude Number with the Corresponding Air Concentrations Prior to Sealing (Weir Control, r/B = 1.5, and t/B = 0.0)

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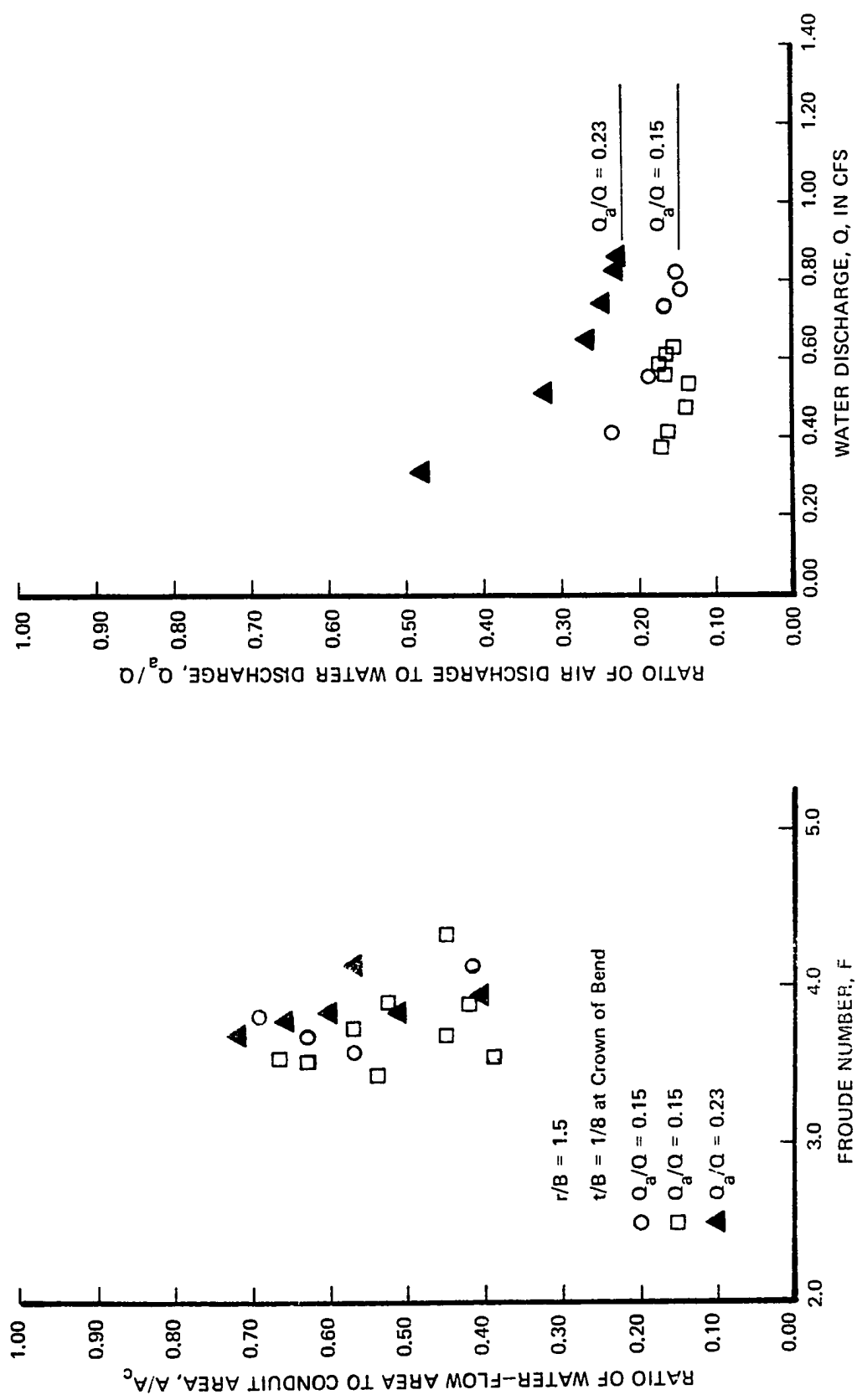

Figure 55. Percent Flow Area Versus Froude Number with the Corresponding Air Concentrations Prior to Sealing (Weir Control, r/B = 1.5, and t/B = 1/8)

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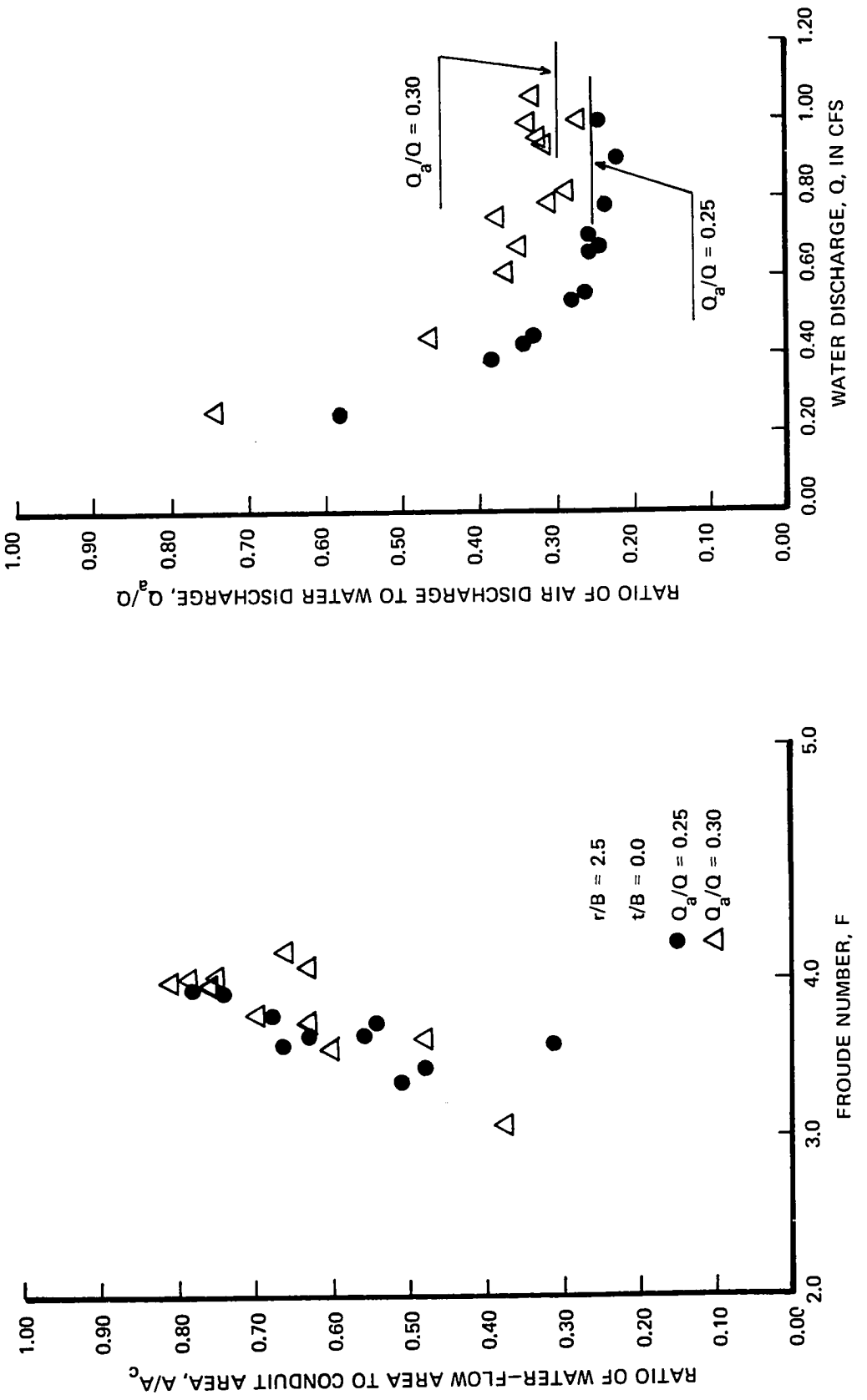

Figure 56. Percent Flow Area Versus Froude Number with the Corresponding Air Concentrations Prior to Sealing (Weir Control, r/B = 2.5, and t/B = 0.0)

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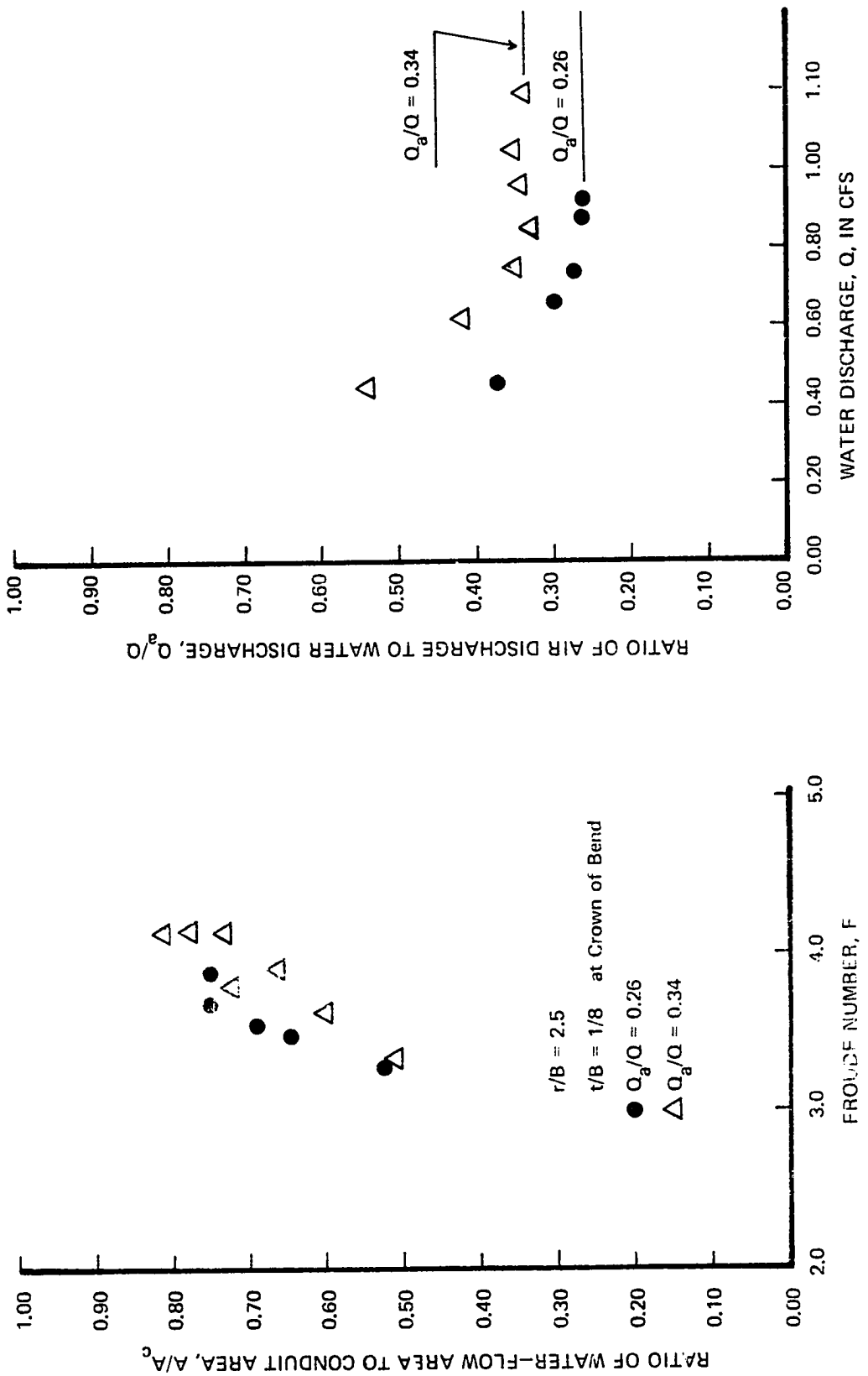

Figure 57. Percent Flow Area Versus Froude Number with the Corresponding Air Concentrations Prior to Sealing (Weir Control, r/B = 2.5, and t/B = 1/8)

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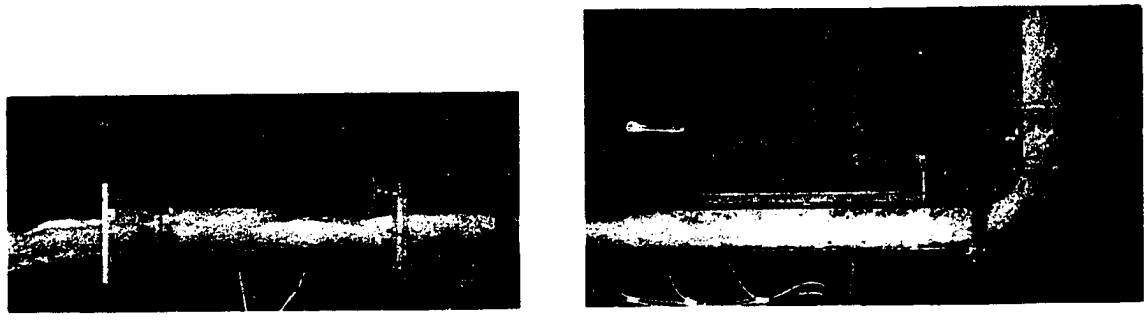
(a) r/B = 0.5, Q = 0.66 cfs and Q_a/Q = 0.42



(b) r/B = 1.5, Q = 0.66 cfs and Q_a/Q = 0.45

(c) r/B = 2.5, Q = 0.66 cfs and Q_a/Q = 0.40

Figure 58. Flow Conditions at the Bend and in the Horizontal Conduit Prior to Sealing (Weir Control)

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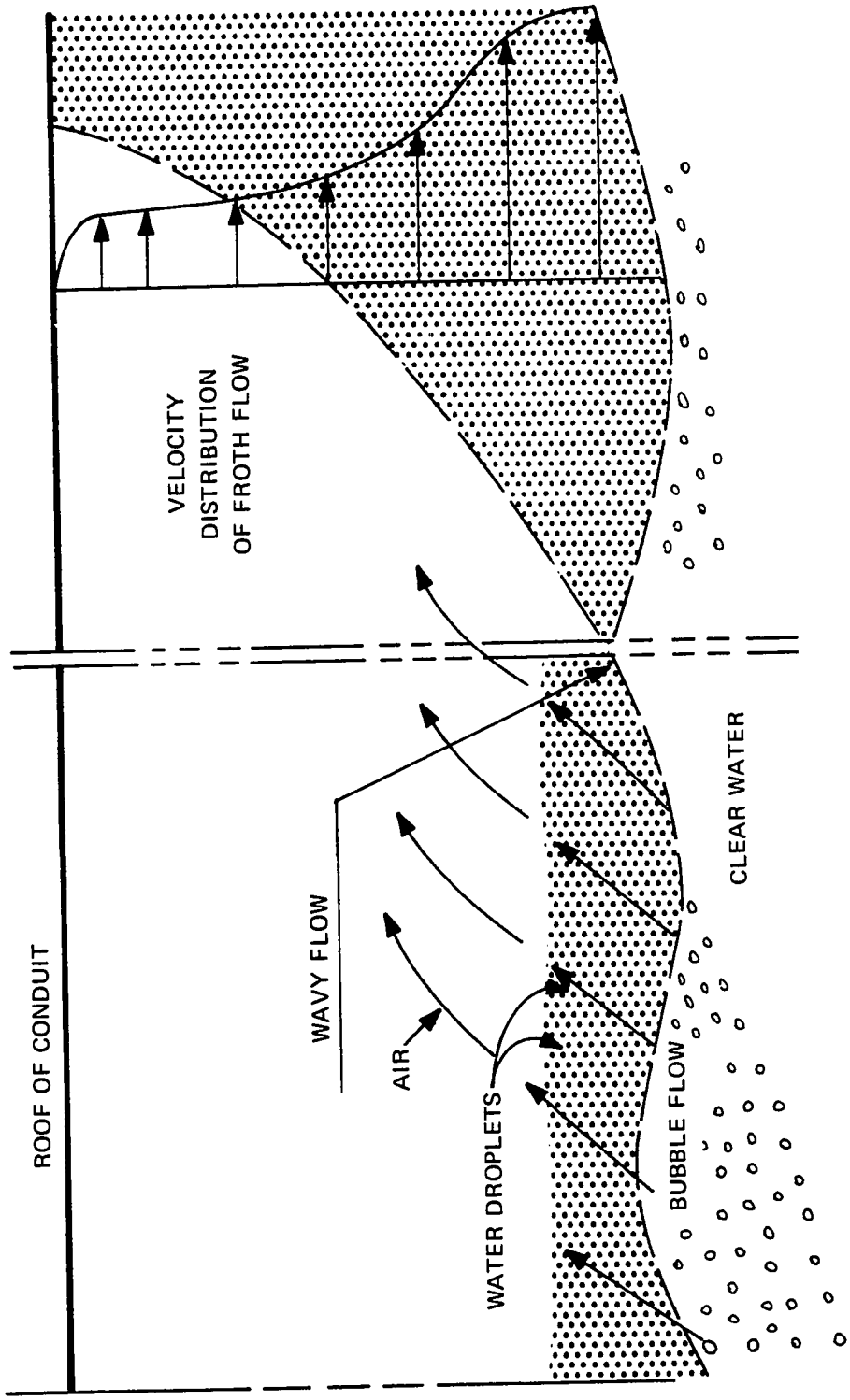

Figure 59. Effect of Froth on Sealing

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long as the layer of froth moves with the velocity of the water flow no sealing occurs.

3. Flow Conditions at Incipient Sealing

Figure 60 shows typical piezometric-head lines along the floor of the conduit at incipient sealing. Figures 61 and 62 show the experimental results. Sealing occurs when the wavy water surface touches the roof. Figure 61 shows that with increasing air concentration, Q_a/Q, less area above the water-flow area is needed at incipient sealing because the air ejecting from the water surface helps to move the water spray with the direction of the water flow and forms a frothy layer over the flow surface that acts as a buffer layer between the wavy flow surface and the roof of the conduit. At the high air concentrations, transition to pipe flow was smooth, since the flow in the conduit was bubble flow with no distinct air-water interface, in contrast to conditions at low air concentrations where the transition was sudden and violent. The wave height at the flow surface is directly related to the Froude number. The larger the Froude number the greater the waves. Figure 62 shows that at larger Froude number, greater concentrations of air, Q_a/Q, are needed to counter the effect of the waves and to form the frothy surface to act as a buffer layer between the flow surface and the roof of the conduit. A deflector at the roof of the upstream end of the conduit suppressed the wave action and thus delayed sealing. With small air concentrations, a deflector at the crown of the bend deflected the flow away from the roof of the conduit and helped delay sealing. With large air concentrations the conduit was full of bubble flow and the deflector at the crown of the bend had

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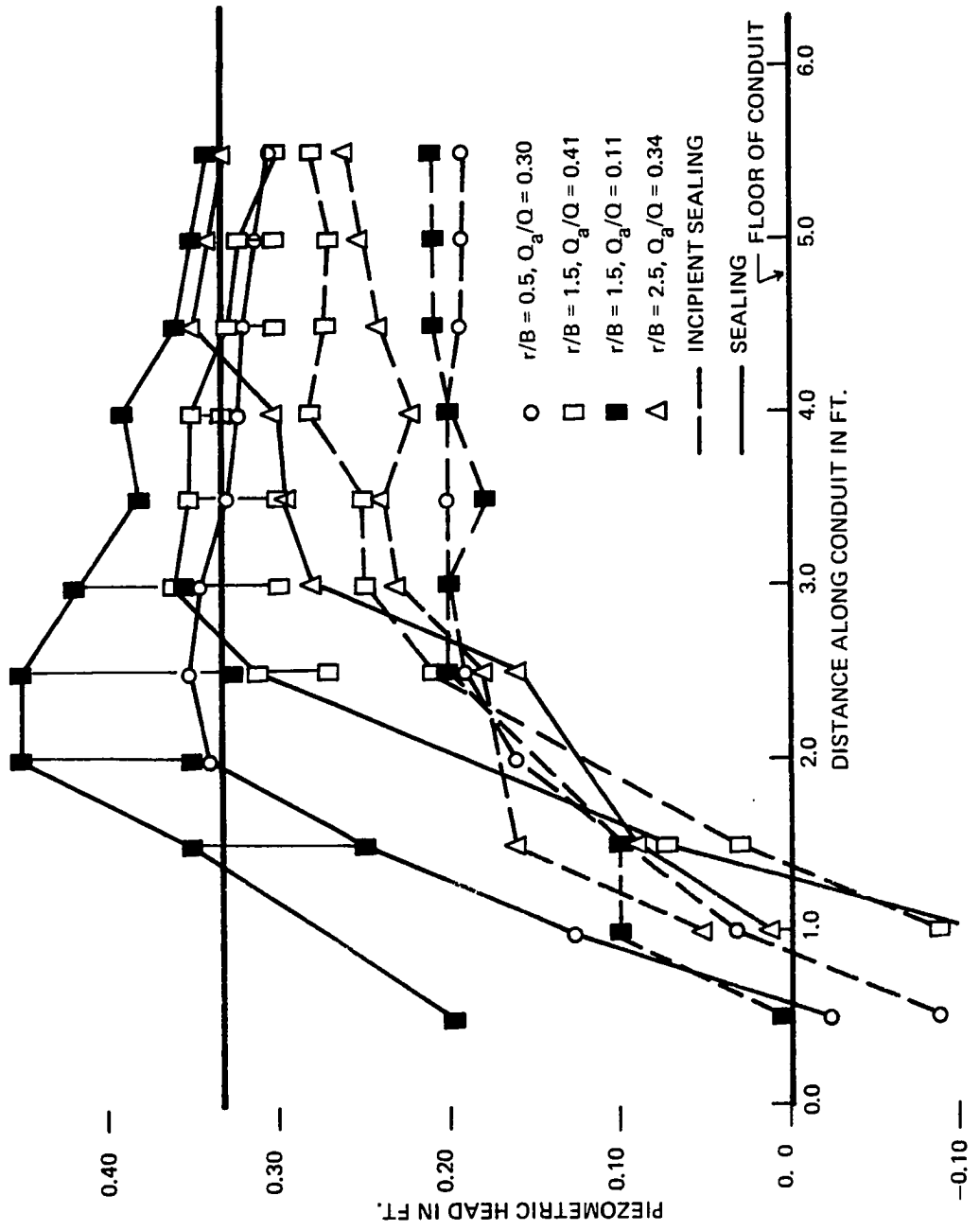

Figure 60. Typical Piezometric-Head Elevations Along Conduit (Weir Control)

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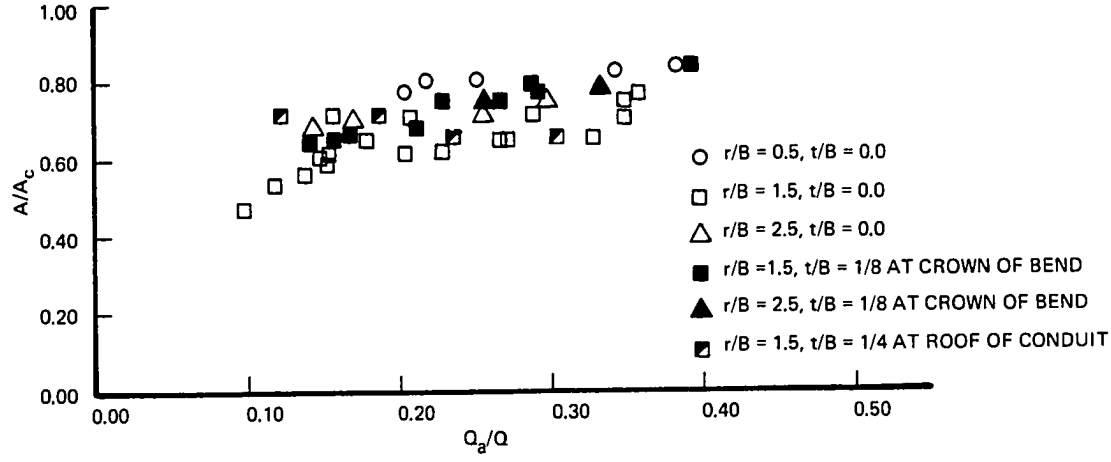

Figure 61. Percent Flow Area Versus Air Concentrations at Incipient Sealing (Weir Control)

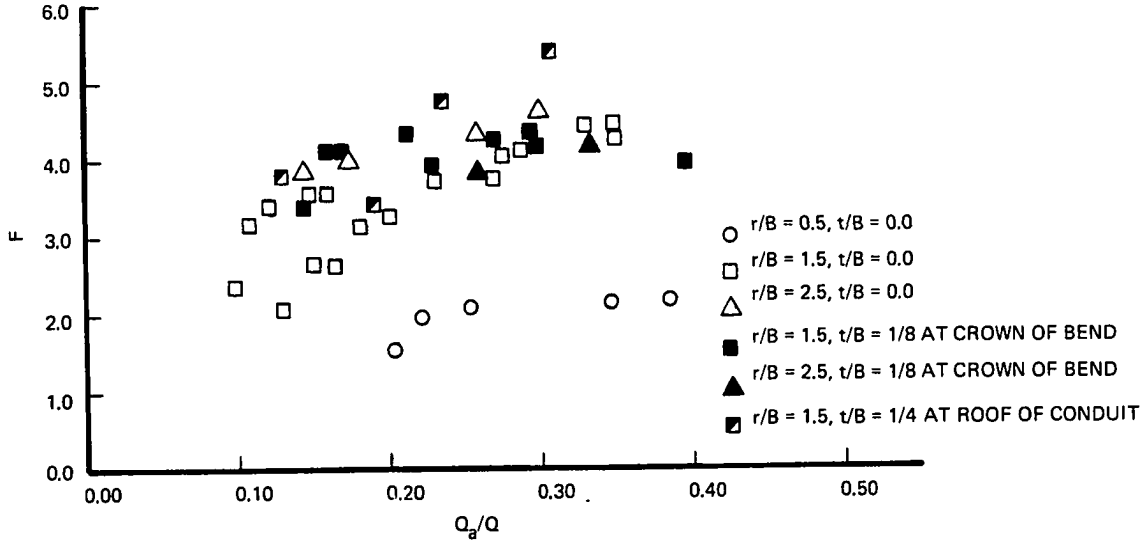

Figure 62. Froude Number Versus Air Concentrations at Incipient Sealing (Weir Control)

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no effect. Qualitative runs were made with the air vents at the roof of the conduit open. With small air concentrations, sealing was delayed because air entering the conduit from the vent substituted for the need of air from the outlet portal and kept the velocity of the inflowing air less than that of the water droplets splashing from the water surface (Figure 49c).

Figure 63 shows the relation between the ratio of the water-flow area to the conduit area and the Froude number. With larger Froude numbers more area is needed above that of the water-flow area to accommodate the waves and the bulking of the flow. With increasing air concentrations less extra area is needed because the frothy surface counters the effect of the waves.

D. Summary

With weir control, transition to orifice control occurs at a ratio of head over the inlet crest to diameter at the crest, H/D_{cr}, approximately equal to 0.25 as shown in Figure 27. The size of the throat and of the vertical shaft also affect the transition to orifice or to short-tube control.

With short-tube control, transition to pipe control depends on the Froude number, F, of the flow in the conduit. With larger Froude numbers, more area is needed above the water-flow area, as shown in Figure 50, to have the velocity of the inflowing air from the outlet portal less than the velocity of the splashing water droplets. The water-flow area depends on the height of the control section at the upstream end of the bend above the floor of the conduit, $r + \frac{B}{2}$, and

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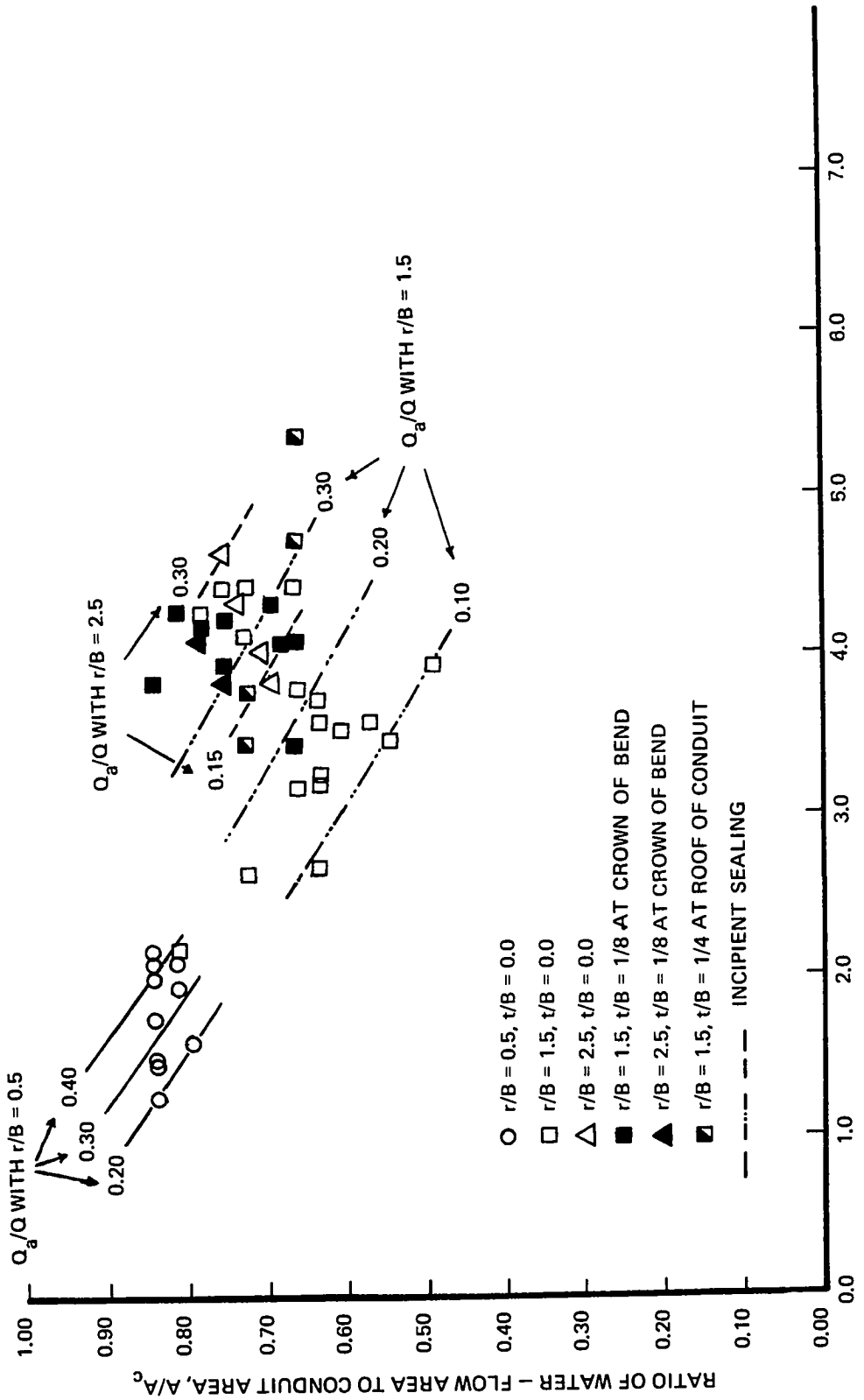

Figrue 63. Percent Flow Area Versus Froude Number at Incipient-Sealing (Weir Control)

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on the horizontal dimension of the vertical shaft, B-t. Conduits downstream of bends with small ratios of r/B or of bends with a deflector flow with a smaller flow area and thus can pass more water discharge with partly-full flow than the conduits downstream of bends with large ratios of r/B or of bends with no deflectors. Air entrainment into the water flow hastens the transition to pipe control and ventilating of the conduit delays the transition.

With weir control, transition to pipe control depends on the Froude number, F, of the flow in the conduit. With larger Froude numbers, more area is needed above that of the water-flow area to accommodate the waves and the bulking of the flow as shown in Figure 63. Bends of small ratios of r/B cause more wave action and hastens the transition. A deflector at the roof of the conduit suppresses the waves and delays the transition. Air entrainment into the water flow dampen the wave action by forming a frothy surface and delays the transition to pipe control. At high air concentrations the transition to pipe flow is smooth in contrast to the conditions at low air concentrations where the transition to pipe flow is sudden and violent.

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CHAPTER V

DISCUSSION

In this chapter a general discussion on shaft spillways is presented.

A. Vertical versus Inclined Shaft Spillway

The type of shaft selected depends on topographic, geologic, economic, and hydraulic considerations.

With the horizontal leg of the spillway embedded into an earth dam, a vertical shaft is used. At narrow rocky sites, topographic suitability at the inlet or the location of the power house or other installations affects the choice between a vertical or inclined shaft.

Geologically, a shaft is preferably excavated at right angle to the bedding planes of the rock to minimize excavation overbreak of the rock.

The choice between an inclined or vertical shaft is also based on economic studies. A vertical or inclined shaft spillway is excavated by first drilling a smaller shaft then enlarging the shaft by extra excavation dumping the excavated material through the already drilled core of the shaft. An inclined shaft excavated at an angle of inclination larger than the angle of repose of rock such as at an angle of 50 degrees so that the rocks can be rolled along the shaft by gravity becomes as easy and as cheap to excavate as a vertical shaft. However, the length of an inclined shaft is shorter than that of a corresponding vertical

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shaft and the portion of the horizontal conduit, subsequently the amount of excavation from an inclined shaft is less which makes the inclined shaft in general cheaper than the vertical shaft.

Hydraulically, a vertical shaft with a 90-degree-angled bend generates more waves onto the free-surface flow in the horizontal conduit than an inclined shaft with a 130-degree-angled bend. Therefore, an inclined shaft spillway is preferable since at a flow with the same Froude number the inclined shaft spillway requires less extra area above the water-flow area. Also, an inclined shaft can drag air along the water surface from the atmosphere at the upstream end of the shaft in contrast to a vertical shaft where the vertical inlet is full of water and air has to enter the conduit from the outlet portal causing sealing of the conduit.

As a conclusion, the inclined shaft is preferred to the vertical shaft.

B. Free versus Submerged Inlet

The purpose of a dam determines the discharge characteristic of a spillway. For the purpose of passing the excess flood water without overtopping the dam, a free discharge over the crest with weir control is necessary. For the purpose of flood control where the discharge is to be limited in the river downstream from the dam, a submerged inlet is required with either orifice or short-tube control.

C. Partly-full versus Full Conduit

Since transition to pipe flow or sealing causes undesirable vibrations of the structure and fluctuations of the flow discharge, the

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conduit should flow partly full throughout the discharge range. However, if the purpose of the dam is flood control with pipe flow as the preferred flow control, then transition to pipe control should be achieved at a low discharge 40/. With the tailwater elevation higher than the outlet elevation (submerged outlet), air entrainment should be kept at a minimum to avoid the possibilities of blow out of air pockets at the outlet 86/.

D. Conduit-Size Determination

1. Discussion of Results

Figure 50 shows the conditions for the upper limit of partly-full flow in a square horizontal conduit with short-tube control and Figure 63 shows the conditions with weir control. The upper limit of partly-full flow depends on the turbulence of the water flow that causes water droplets to break away from the surface, on the waves over the flow surface, and on the velocity of the inflowing air from the outlet portal. With higher water velocities and greater waves over the flow surface, more space above the water-flow area is needed to accommodate the waves and to increase the inflowing air-flow area to keep the inflowing air velocity smaller than that of the splashing water droplets. A wavy-surface flow demands more extra space above the water-flow area than a corresponding smooth-surface flow as can be seen by comparing Figures 50 and 63.

Factors affecting the turbulence in the flow or the waves affect the upper limit for partly-full flow. With short-tube control where the flow surface is smooth, roughness of the concrete surface or irregularities at the joints cause increased turbulence in the flow that results

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in more water droplets splashing against the roof. The inflowing air from the outlet portal can hasten sealing of the conduit. Ventilation from the upstream end of the conduit decreases the air demand from the outlet portal reducing the velocity of the inflowing air thereby delaying sealing. With weir control where the flow surface is wavy, highly aerated flow forms a frothy surface that counters the wave action. The air that ejects from the flow forms an air current in the direction of the water flow thereby reducing the air demand from the outlet portal.

Figures 50 and 63 for square conduits are reasonable to use with circular conduits. The phenomenon of sealing with the water droplets breaking away from the water surface and air flowing into the conduit from the outlet portal or with the waves touching the roof is the same in both the circular and the square conduit. With flow in circular conduits more wave action and surface disturbances are expected because of the tendency that the flow turn along the arched roof onto the main stream of flow. Therefore, in a circular conduit it is reasonable to allocate more space area above the water surface than in a rectangular conduit. If the values of A/A_c for the rectangular conduit of this investigation are applied to circular conduits somewhat more space is required to compensate for the additional wave action and surface disturbances.

With a flow deflector at the outlet portal, there exists the possibility of a hysteresis phenomenon where a hydraulic jump can occur in the conduit as the discharge is decreased thus sealing the conduit as was demonstrated by Abecasis and Quintela 87/.

Since similarity criteria for turbulence and air demand are

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inadequately established, these experimental results should be used only for initial selection of near optimum designs.

2. Design Criterion

Sealing of the horizontal conduit depends on the Froude number of the flow. Figure 50 shows the relation of Froude number, F, to A/A_c for short-tube control. The required ratio of A/A_c can be achieved by the proper choice of bend and deflector combination as was demonstrated experimentally and solved for analytically by Ambrose 80/. The existing shaft spillways of Table A-3 of Appendix A with circular conduit are in fair agreement with the suggested limit (Figure 50) as shown in Figure 64. Figure 63 shows the experimental results with weir control and Figure 65 shows the same information for existing spillways. Inclined shaft spillways generate less wave action and are ventilated from the inlet. The upper limit of partly-full flow conditions for an inclined shaft approach those for a vertical shaft with short-tube control. The criterion of the Portugese National Civil Engineering Laboratory (L.N.E.C.) 13/ of allowing 86 per cent water-flow area and of the U.S. Bureau of Reclamation (U.S.B.R.) 12/ of allowing 75 per cent water-flow area are also in agreement with the suggested criterion since the L.N.E.C. and the U.S.B.R. spillways operated at Froude numbers not exceeding the limit of Figures 50. Since the L.N.E.C. and the U.S.B.R. limits of flow area in the conduit are specific limits found from experience with specific model studies without differentiating between weir control and short-tube control, these limits can not be general.

E. Bend Curvature

With short-tube control, the bend and the deflector determine

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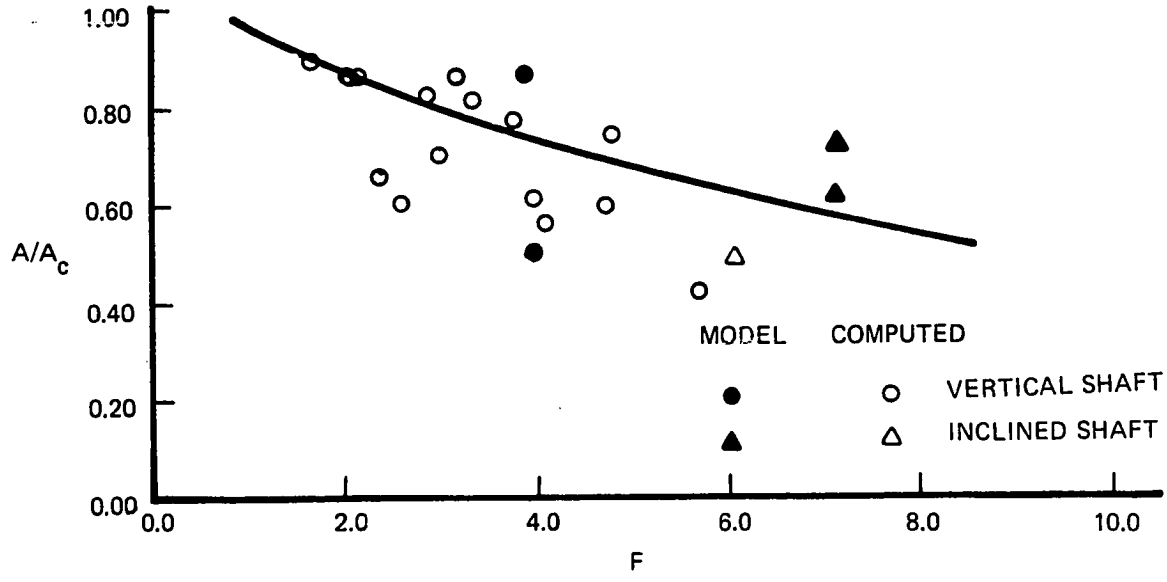

Figure 64. Comparison of Existing Shaft Spillways with Suggested Criterion (Short-Tube Control)

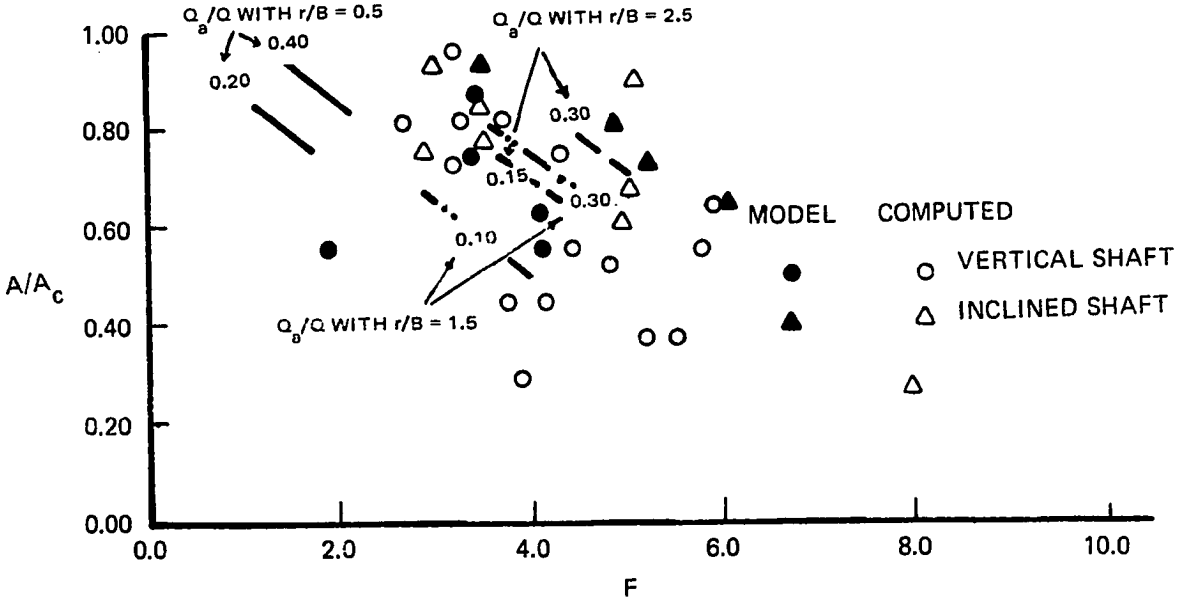

Figure 65. Comparison of Existing Shaft Spillways with Suggested Criterion (Weir Control)

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the depth of flow in the horizontal conduit. The depth of flow depends on the vertical distance between the line of flow separation at the upstream end of the bend and the floor of the conduit, $r + \frac{D_c}{2}$, and on the diameter of the vertical shaft, D-t. From Ambrose's analysis 80/, a bend of small ratio of r/D_b acquires a smaller flow area than a bend of large ratio of r/D_b, consequently would seal at a higher Froude number.

With weir control, a bend of small ratio of r/D_b generates larger waves than a bend of large ratio of r/D_b. Accordingly, for a higher Froude number flow a vertical bend with r/D_b ratio larger than 2.0 is recommended. Figure 66 shows the relation of Froude number to bend curvature, r/D_b, for the existing shaft spillways of Table A-3 of Appendix A. Figure 66 shows the confusion among the designers in choosing a bend curvature. For inclined shaft spillways the U.S. Bureau of Reclamation suggests a bend curvature of at least $r/D_b = 8.0$ 88/.

F. Air Demand

Air demand of a shaft spillway is that amount of air dragged out with the outflowing water flow which has to be replenished either from the outlet portal, from an air vent in the conduit, or from the air entrained into the flow at the pool surface. An inflowing air current from the outlet portal in an opposite direction to the water flow causes sealing of the conduit since it deflects the splashing water droplets which choke the space above the water flow. After the air-velocity profile is established the length of the conduit has no effect on the discharge of the inflowing air since the discharge is the product of the velocity times the flow area.

Formulation of air demand in relation to flow parameters such as

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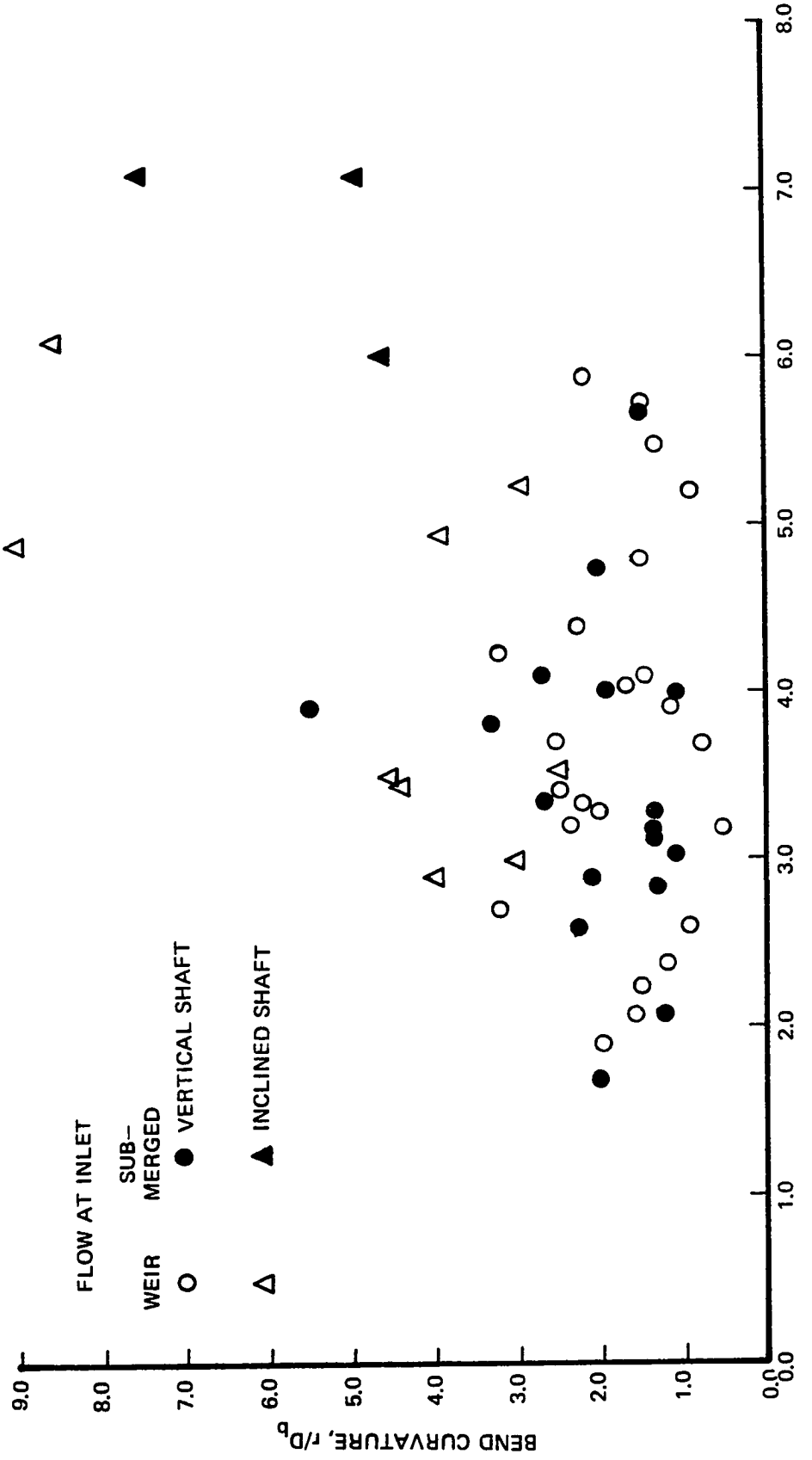

Figure 66. Relation of Bend Curvature to Froude Number for Existing Shaft Spillways

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Froude number could not be achieved in this investigation because only pressure measurements were made. However, Campbell and Guyton 51/ attempted to formulate the air demand theoretically but were unsuccessful because they could not estimate the value of the drag force acting on the air flow. Instead, Campbell and Guyton measured the air demand through an air vent in gated outlet works and related it to Froude number minus one for conditions prior to sealing. Ghetti and Di Silvio 56/ tried to determine the total air demand from the outlet portal and from an air vent in the conduit and to study the effect of the air vent size on the air movement in outlet works. To delay sealing, the air layer above the water surface should flow in the same direction of the water flow.

The air entrained into the flow from the pool surface serves to form a frothy surface in the horizontal conduit and to aerate the conduit. Although the air segregates from the water flow along the length of the conduit, the air ejecting from the water surface eventually forms an air current above the water surface which helps delay sealing. Aeration of the flow cushions the impact of the water on the floor of the vertical bend 7/, reduces cavitation damage 39/, leads to greater and more efficient dissipation of energy in the stilling basin downstream of the horizontal conduit 47/, and increases the total head losses in the spillway as compared to a non-aerated flow 89/. However, with short-tube control, air entrainment into the flow hastens sealing in contrast to conditions with weir control.

Special measures should be taken to entrain air since only small amounts of air are entrained from the pool surface by the falling water

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as shown in Figure 29 and at an air vent at the throat of a shaft as shown in Figure 30 at about incipient-sealing conditions. One measure is to build the crest profile in a stepped shape as that of Lady Bower shaft spillway 5/ and as is shown in Figure 67. The prototype behavior of Lady Bower shaft spillway was described as:

> It has been noted that when the spillway is discharging heavily the cascade of broken water falling down the shaft acts as an air pump and produces an air current charged with spray, which discharges out the lower end of the tunnel in considerable volume. Contrary to expectations, the discharge is slightly greater for a given head with the stepped morning-glory than with a smooth one. The spillways have proved a highly efficient method of discharging overflow water from the reservoir and they are entirely reliable for that purpose.

G. Design Examples

The following design examples are considered to illustrate the use of the suggested design criteria of Figure 50 and Figure 63 in choosing an initial near optimum conduit size and a suitable bend. The flow conditions of Hearte Butte shaft spillway, as shown in Figure 31, are chosen for illustration. The purpose of the dam was flood control. The maximum discharge with weir control is 3000 cfs and the maximum discharge with submerged short-tube control is 5600 cfs.

1. Design for Short-tube Control

Using a constant-diameter conduit of the same dimension as of the vertical shaft, D_c = 11.0 ft. The conduit area becomes $A_c = \pi D_c^2/4$ = 154 ft^2. Assume A/A_c = 0.75, then A = 116 ft^2, V = 48 fps, hydraulic depth = 7.1 ft, and F = 3.18. Figure 50 shows that the flow with F = 3.18 and A/A_c = 0.75 is a little less than at incipient-sealing conditions. A/A_c = 0.75 corresponds to d/D_c = 0.70. From Ambrose analysis

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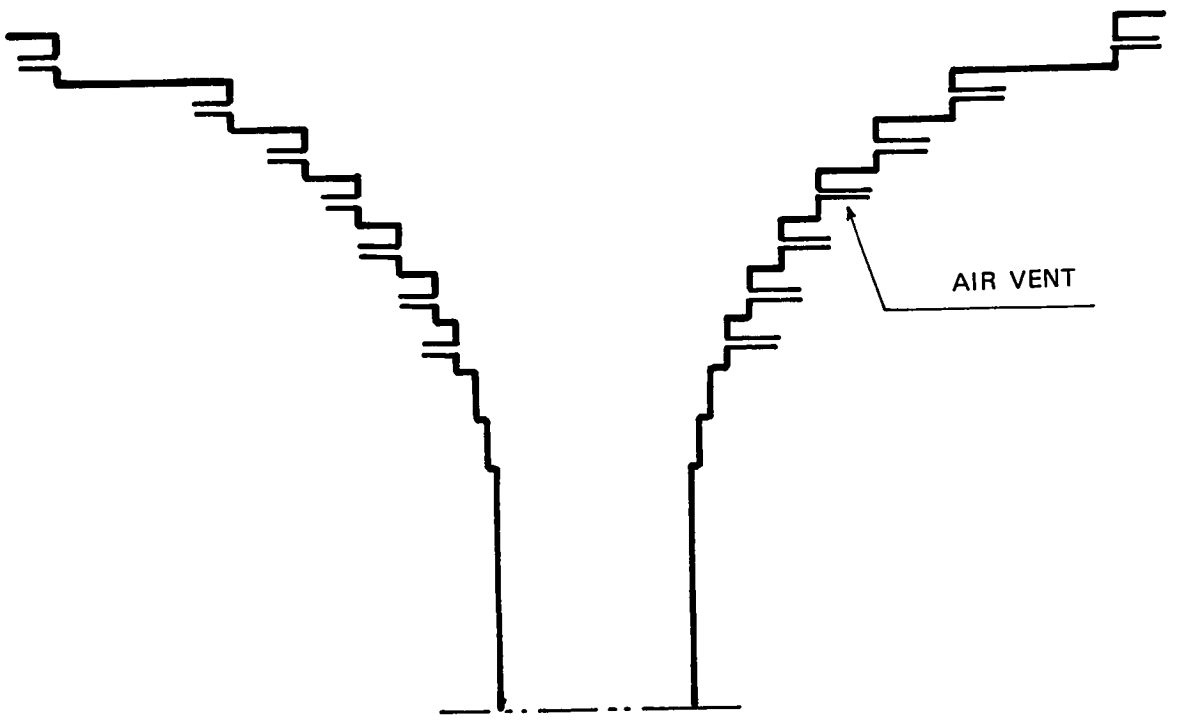

Figure 67. Stepped-Crest Profile

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80/ for $d/D_c = 0.70$ the value of $(r + D/2)/D$ is equal to 1.5 which corresponds to a bend curvature $r/D_b = 2.0$ similar to the actual design.

2. Design for Weir Control

A check for partly-full flow conditions with weir control is necessary to assure that the conduit will not seal. At Q = 3000 cfs the height of the pool surface is 6 ft above the spillway crest.

For the shaft; A = 145 ft^2, V = 19.5 fps, and $V^2/2g$ = 5.9 ft. Assume entrance loss coefficient $K_{ent.} = 0.1$, bend loss coefficient $K_b = 0.1$, and Mannings' roughness coefficient n = 0.018. Friction loss coefficient $K_f = \frac{29.1\ n^2 L}{R^{4/3}}$.

$$K_f = \frac{29.1 \times (0.018)^2 \times 31}{2.92} = 0.1$$

Total loss coefficient for the shaft portion, K = 0.3 and h_L = 1.77 ft.

For the conduit portion; assume $d/D_c = 0.50$, then $A/A_c = 0.50$, A = 77 ft^2, V = 39 fps, and $V^2/2g$ = 23.7 ft. Friction loss coefficient $K_f = \frac{29.1\ n^2 L}{R^{4/3}} = \frac{29.1 \times (0.018)^2 \times 625}{3.82} = 1.55$ and h_L = 36.6 ft.

From energy considerations

$$d + h_L + \frac{V^2}{2g} = H_c + H$$

$$5.5 + 36.6 + 1.77 + 23.7 \cong 61.7 + 6$$

Therefore the hydraulic depth = 4.3 ft and F = 3.3. Figure 63 shows that flow conditions with F = 3.3 and $A/A_c = 0.50$ are well below incipi-

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ent-sealing conditions.

It is a good design practice to insert a deflector at the crown of the bend so as to fix the flow control at the bend in case the flow shifts to short-tube control. The deflector helps keep the horizontal conduit flowing partly-full.

H. Summary

The results of this study are not aimed at eliminating the need for model studies of shaft spillways but rather to enable the designer to make better initial designs. Appreciable cost reductions can be made on shaft-spillway model construction by initial selection of near optimum designs because overly conservative designs add to construction cost. Unsafe designs which are detected during model tests require additional time and costs for revised design and model tests. For small spillways, where model studies are too costly, the experimental results can be used for safe near-optimum designs.

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CHAPTER VI

CONCLUSIONS

This investigation has clearly demonstrated the role of the bend curvature, deflector, and air concentration on the phenomenon of sealing or transition to pipe control in the horizontal leg of a vertical-shaft spillway. The following conclusions can be made:

First, sealing of the horizontal conduit depends on the Froude number of the flow. To maintain partly-full flow in the horizontal conduit more space above the water-flow area is needed with an increase of Froude number. Additional extra space is needed with wavy-surface flow or with aerated flow. With short-tube control, the bend curvature, r/D_b, and the deflector thickness determine the maximum water-flow area in the conduit.

Second, with short-tube control, bends of small ratios of r/D_b pass more discharge at partly-full flow in the conduit than bends of large ratios of r/D_b because the flow area in the conduit is smaller. With weir control, bends of smaller ratios of r/D_b generate more waves.

Third, with short-tube control, aeration of the flow bulks the flow and hastens sealing. With weir control, aeration of the flow forms a frothy surface that dampen the waves. Ventilation of the conduit from the outlet portal causes an inflowing air current into the conduit in the opposite direction of the water flow which leads to sealing of the conduit. Ventilation from the upstream end of the conduit causes the

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air current to flow with the direction of the water flow and delays sealing.

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CHAPTER VII

RECOMMENDATIONS

In this investigation, the air demand from the outlet portal could not be measured or formulated nor could the air concentration in the flow be scaled to the prototype. The following recommendations are suggested:

First, a study of the air demand from the outlet portal and the effect of the air vent size at the upstream end of the conduit on the air movement in the space above the water area is recommended.

Second, a study for a similarity criterion for air entrainment in water flow is needed.

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APPENDIX A

TABLES

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TABLE A-1

DATA ON EXISTING SHAFT SPILLWAYS

Index No.	Dam			Shaft Spillway					Bend		Conduit	Reference ‡
	Name	Location	Year Completed	Type Of Shaft	H_c,ft	Q,cfs	H,ft	D_{cr},ft	r,ft	D_b,ft	D_c,ft	
	USBR-USA											
1	Hoover	Nev.-Ariz.	1936	Inclined	574.6	200,000			225.0	50.0	50.0	1
2	Glen Canyon	Ariz.		Inclined	513.8	138,000	63.0		350.0	41.0	41.0	2,3
3	Hungry Horse	Mont.	1953	Inclined	475.5	53,000	16.9	64.0	120.0	24.5	24.5*	3,4,5
4	Yellowtail	Mont.		Inclined	421.8	92,000	67.0		290.0	32.0	32.0	3,6
5	Flaming Gorge	Colo.		Inclined	401.0	28,750	39.0		200.0	18.0	18.0	3
6	Trinity	Calif.	1962	Inclined	408.15	24,000	17.1	53.0	150.0	20.0	20.0	3,7
7	Owyhee	Idaho	1932	Vertical	313.0	30,000	12.0	60.0	50.0	22.5	22.5	3,8,9
8	Whiskeytown	Calif.		Vertical	253.0	28,650	10.5	92.0	115.5	21.0	21.0	10
9	Monticello	Calif.	1957	Vertical	245.0	48,500	15.5	72.0	90.0	28.0	28.0	3
10	Palisades	Idaho	1957	Inclined	200.0	48,500	51.0		124.0	28.0	28.0	3,11
11	Kortes	Wyo.	1951	Inclined	197.0	50,000	23.7		75.0	30.0	30.0	3
12	Seminoe	Wyo.	1939	Inclined	152.39	48,500	50.0		90.0	30.0	30.0	3
13	Horse Mesa	Ariz.	1927	Inclined	149.5	150,000	44.5		85.5	30.0	30.0	3
14	Joes Valley	Utah		Inclined	174.7	5,000	8.3	24.1	60.0	13.0	13.0	12
15	Gibson	Mont.	1930	Vertical	162.0	50,000	20.0	92.0	59.0	29.5	29.5	3,8,9
16	Spangler	Idaho		Vertical	133.0	3,885	8.1	31.21	25.0		11.0	13
17	Little Panoche	Calif.		Vertical	94.5	3,220	28.9	30.0	20.0	7.5	9.5	14
18	Hearte Butte	N. Dak.	1949	Vertical	61.8	5,600	53.7	32.5	21.0	11.0	14.0	15,16
19	Guernsey	Wyo.	1927	Vertical	86.0	25,800	15.0	110.0	29.5		30.0	3
20	San Luis	Calif.		Vertical	102.1	900	1.85	31.0	19.0	9.5	9.5	17
21	Shade Hill	S. Dak.	1950	Vertical	55.62	5,000	40.0	31.5	14.0	13.5	13.5	3,16
22	Arbuckle	Okla.		Vertical	58.0	3,410	28.9	22.33	12.5		9.5	13
23	Foss	Okla.	1961	Vertical	59.2	3,700	22.4	22.33	12.5		9.5	3
24	Sherman	Neb.	1962	Vertical	73.83	1,095	7.7	13.17	12.0		8.0	13
25	Cheney	Kansas		Vertical	58.88	3,000	18.8	22.33	25.5		9.5	13
26	Ft. Cobb	Okla.	1959	Vertical	55.45	3,050	19.6	22.33	12.5		9.5	13
27	San Luis Forebay	Calif.		Vertical	67.0	3,250	3.0	60.5	16.79	11.75	11.75	18
28	Red Willow	Neb.	1962	Vertical	45.59	4,860	23.1	31.5	14.0		13.5	13
29	Norman	Okla.		Vertical	53.41	2,840	15.3	22.33	12.5		9.5	13
30	Jamestown	N. Dak.	1953	Vertical	54.6	2,930	10.3	22.33	12.5		9.5	3
	T.V.A.,USA											
31	Fontana	N.C.	1944	Inclined	405.0	100,000	45.0		100.0	34.0	34.0	19,20
32	Watauga	Tenn.	1948	Vertical	307.6	60,000	13.0	128.0	75.0	34.0	34.0	21
33	South Holston	Tenn.	1950	Vertical	260.8	60,000	13.0	128.0	75.0	34.0	34.0	21

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TABLE A-1 (Continued)

DATA ON EXISTING SHAFT SPILLWAYS

Index No.	Dam			Shaft Spillway					Bend		Conduit	Reference‡
	Name	Location	Year Completed	Type Of Shaft	H_c,ft	Q,cfs	H,ft	D_{cr},ft	r,ft	D_b,ft	D_c,ft	
	Corps of Engineers, USA											
34	Eau Galle	Wisc.		Vertical	25.0	4,800	80.0	25.0	Streamlined		9.75**	22
35	Fort Peck	Mont.	1940	Vertical							24.75	23
36	Pleasant Hill	Ohio	1938	Vertical								24
	Others-USA											
37	Davis Bridge	Vt.	1924	Vertical	185.0	27,000	8.0	80.0	55.0	22.5	21.5	25,9
38	Bouquet	Calif.	1934	Vertical	164.0	1,600	5.0	16.0	16.0	8.0	8.0	26
39	Kingsley	Neb.	1942	Vertical	120.0	54,000	28.0	90.0	64.0	28.5	28.5	27,9
40	San Pablc	Calif.	1920	Vertical	166.0	900	5.0	33.0			14.5	28
41	Round Butte	Oreg.		Inclined		28,200					21.0	29
	National Laboratory of Civil Engineering (LNEC), Portugal											
42	Paradela	Portugal		Vertical	362.0	29,900	10.2	78.6	65.5	20.4	25.6	30,31,32
43	Miranda	Portugal		Inclined	239.0	45,700	16.2	65.6	116.5	29.5	29.5	30,32
44	Pego do Altar	Portugal		Vertical	178.0	35,200	11.5	139.5	41.0	34.2	34.2	30,33
45	Pracana	Portugal		Vertical	177.0	58,000	26.2	64.4	65.6	31.2	31.2**	30,33
46	Maranhão I	Portugal		Vertical	162.0	56,400	12.8	141.0	51.7	34.4	34.4	30,34
47	Maranhão II	Portugal		Inclined	147.5	56,400	19.4	82.0	140.0	34.4	34.4	30,34
48	Silves	Portugal		Vertical	137.5	28,200	11.5	78.8	47.5	29.5	29.5	30,32
49	Montagril	Portugal		Vertical	119.5	26,900	12.6	67.5	32.8	26.6	26.6	30,34
50	Campilhas	Portugal		Vertical	66.5	7,400	9.5	24.0	32.8	16.4	16.4	30,33
	International											
51	Sulak	USSR	1935	Vertical	656.0	60,000	13.0	211.0		31.0	36.0	35
52	Phumiphol	Thailand		Inclined	400.0	105,500					37.0	36
53	Dez No. 2	Iran		Vertical	346.0	106,000	65.5				41.3	37
54	Dez No. 1	Iran		Vertical	230.0	106,000	65.5				45.9	37
55	Mibora	Japan		Inclined	334.0	71,000	59.0				32.8	38
56	San Esteban	Spain		Inclined	330.0	19,400	24.6			23.0	27.8**	39
57	Menjil	Iran	1952	Vertical	272.0	98,500	14.4	120.0	75.5	26.2	26.2	40
58	Geehi	Australia		Inclined	250.0	55,000	13.0	105.0			29.0	38
59	Jubilee	Hong Kong		Inclined	265.0	17,000	8.0	74.0	45.0	25.0	15.0	41
60	Ben Metir	Tunisia	1953	Vertical	148.0	21,800	49.0	35.0		21.0	19.7	42

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TABLE A-1 (Continued)

DATA ON EXISTING SHAFT SPILLWAYS

Index No.	Dam			Shaft Spillway					Bend		Conduit	Reference‡
	Name	Location	Year Completed	Type Of Shaft	H_c,ft	Q,cfs	H,ft	D_{cr},ft	r,ft	D_b,ft	D_c,ft	
61	Narugo	Japan		Inclined	206.0		27.8		141.0	21.3	21.3	43
62	Shing Mun	Hong Kong		Vertical	223.0	20,000	5.95		40.0	20.0	18.0	44
63	Dokan	Iraq	1956	Vertical	226.0	63,500	16.4	132.0	20.5	41.0	33.6	45,46
64	Sion	USSR		Vertical	210.0	14,400						35,47
65	Maraetal	N. Zealand		Inclined	200.0	30,000					25.0	48
66	Jirkov	Czech.		Vertical	164.0	2,460	3.94		32.8		9.85	49
67	Ebenezer	U.S. Africa		Vertical	158.0	22,000	10.5	63.0	50.0	20.0	33.75†	50
68	Alakır	Turkey		Vertical	80.0	5,300	74.0	26.6	29.0	12.8	16.4	51
69	San Roque	Argentina	1944	Vertical	112.5	10,000	25.27	66.93	32.81	13.1	13.1	52
70	Fassideri	Greece	1952	Vertical	123.48	10,700	4.92	98.5	39.4	15.1	15.1	53
71	Lady Bower	England	1944	Vertical	122.0	10,000	6.5	80.0	35.0	15.0	14**	9,54
72	Marèges	France		Inclined	84.0	35,200	36.0					55
73	Sainte-Cecile d'	France		Vertical	113.5		13.8					55
74	Regadera	Colombia	1935	Vertical	97.7	15,000	9.0	55.0		36.5	20.3††	9
75	Burnhope	England		Vertical	103.5	2,600	2.7	50.0	16.0	12.0	12.0	9
76	Castillon	France		Inclined	93.5		12.1					55
77	Hracholuskey	Czech.		Vertical	94.0	9,300	9.2	47.5		20.6		49
78	Taf Fechon	Wales	1927	Vertical	100.2	3,000	2.8	66.0	15.0	16.0	13.5	9
79	Manuherikia	N. Zealand	1935	Vertical	90.0	15,000	6.0	102.0	25.5	17.0	17.0	9
80	Akongtein	Taiwan	1951	Vertical	70.0	3,250	11.5	60.0		9.8	9.8	9
81	Stratwaich	Scotland		Vertical	65.0	3,250	4.0					47
82	Pontian Ketchil	Singapore	1931	Vertical	59.5	2,700	2.7	50.0	10.0	13.0	13.0	9
83	Silent Valley	Ireland	1926	Vertical	54.6	2,500	2.3	80.0	18.0	16.0	16.0	9
84	San Dalmazzo	Italy		Vertical	190.0							47
85	Canal Boissons	Italy		Vertical		1,130	2.46	25.0		8.0	8.0	47
86	Tenda	Italy		Vertical								47
87	Blacton	England	1896	Vertical								47
88	Front	England	1908	Vertical								47
89	Galloway	England		Vertical		4,000	4.5	38.0		11.6	11.6	47
90	Švihov	Czech.		Vertical		19,700						49
91	Krauset Bauden	Czech.	1911	Vertical			3.48			16.5	16.5	47
92	Konigreich Walder	Czech.	1911	Vertical								47
93	Bojkovice	Czech.		Vertical								49
94	Lumot	Phillipines	1949	Vertical		7,060						9
95	L'oued Sorno	Algeria		Vertical		12,700					19.7	47
96	Aldeadavila	Spain		Vertical		98,500						56

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TABLE A-1 (Concluded)

DATA ON EXISTING SHAFT SPILLWAYS

‡ References are given in REFERENCES of TABLE A-1 in APPENDIX-A
* At the outlet the diameter becomes 31 ft. horse shoe section
** Horse-shoe section
† Polygonal section
†† Elliptic Section

Symbols

H_c Difference of elevation between inlet crest and outlet invert, ft.
Q Design discharge of spillway, cfs.
H Head over inlet crest at design discharge flow, ft.
D_{cr} Diameter of inlet crest, ft.
r Radius of the bend measured till centerline of bend section, ft.
D_b Diameter of the bend, ft.
D_c Diameter of the circular horizontal conduit, ft.

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TABLE A-2

STRUCTURAL AND OPERATIONAL CHARACTERISTICS
OF EXISTING SHAFT SPILLWAYS OF TABLE A-1

Index No.	Spillway		Auxiliary Structural Elements				Prototype Observations		Remarks
	Name	Type*	Deflector	Air Vent	Inlet	Anti-Vortex Arrangement	Vibration	Noise	
	U.S.B.R.-USA								
1	Hoover	I	None	None	Ungated				Prototype inspected at Q = 38,000 cfs.
2	Glen Canyon	I	None	None	Gated				
3	Hungry Horse	I	At throat of shaft	below deflector	Gated	ring gate			Prototype inspected at Q = 30,000 cfs.
4	Yellowtail	I	None	None	Gated				
5	Flaming Gorge	I	None	None	Gated				
6	Trinity	I	At crown of bend	below deflector	Ungated	3 vertical rib vanes in shaft and on crest pier			
7	Owyhee	V	None	At crest of inlet	Gated	ring gate	None	None	Prototype inspected at Q = 20,000 cfs.
8	Whiskeytown	V	At crown of bend	below deflector	Ungated	Six rib vanes on crest and extending down into the crest profile			
9	Monticello	V	None	None	Ungated	None			
10	Palisades	I	None	None	Gated				
11	Kortes	I	None	None	Ungated				
12	Seminoe	I	None	None	Gated				
13	Horse Mesa	I	None	None	Gated				
14	Joes Valley	I	At throat of shaft and at crown of bend	below deflector	Ungated	2 crest piers and finger berm			
15	Gibson	V	None	None	Gated	6 radial gates with 6 piers	None	Considerable	Prototype inspected at Q = 13,100 cfs.

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TABLE A-2 (Continued)

STRUCTURAL AND OPERATIONAL CHARACTERISTICS
OF EXISTING SHAFT SPILLWAYS OF TABLE A-1

Index No.	Spillway		Auxiliary Structural Elements				Prototype Observations		Remarks
	Name	Type*	Deflector	Air Vent	Inlet	Anti-Vortex Arrangement	Vibration	Noise	
16	Spangler	V							
17	Little Panoche	V	At bend	below de-	Ungated	None			
18	Hearte Butte	V	At crown of bend	At throat of shaft	Ungated	6 piers	None	None	Prototype inspected at Q = 3,800 cfs.
19	Guernsey	V	None	None	Gated	2 drum gates			
20	San Luis	V	At bend	below deflector	Ungated	None			
21	Shade Hill	V	At bend	below deflector	Ungated	6 piers	None	None	Prototype inspected at Q = 5,020 cfs.
22	Arbuckle	V							
23	Foss	V							
24	Sherman	V							
25	Cheney	V							
26	Ft. Cobb	V							
27	San Luis Forebay	V	At bend	below deflector	Ungated	None			
28	Red Willow	V							
29	Norman	V							
30	Jamestown	V							
	T.V.A.-USA								
31	Fontana	I	None	None	Gated				
32	Watauga	V	At crown of bend	None	Ungated	6 piers			
33	South Holston	V	At crown of bend	None	Ungated	6 piers			
	Corps of Engineers-USA								
34	Eau Galle	V	None	None	Ungated				
35	Fort Peck	V			Gated				

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TABLE A-2 (Continued)

STRUCTURAL AND OPERATIONAL CHARACTERISTICS
EXISTING SHAFT SPILLWAYS OF TABLE A-1

Index No.	Spillway		Auxiliary Structural Elements				Prototype Observations		Remarks
	Name	Type*	Deflector	Air Vents	Inlet	Anti-Vortex Arrangement	Vibration	Noise	
36	Pleasant Hill	V							
	Others-USA								
37	Davis Bridge	V	None	None	Ungated	16 piers	None	None	Prototype inspected at Q = 19,400 cfs.
38	Bouquet	V	None	None	Ungated	None			
39	Kingsley	V	None	None	Gated	12 tractor gates and piers	None	None	Prototype inspected at Q = 4,500 cfs.
40	San Pablo	V			Gated				
41	Round Butte	I			Gated				
	I.N.E.C.-Portugal								
42	Paradela	V	At crown of bend	below deflector					
43	Miranda	I	None	None					
44	Pego do Altar	V	At crown of bend	below deflector	Gated	4 tainter gates	None	None	Prototype inspected at Q = 915 cfs.
45	Pracana	V	At upstream end of conduit	below deflector	Gated	Cylinder gate and 6 piers	None	None	Prototype inspected at Q = 5,200 cfs.
46	Maranhão I	V	At downstream end of bend	after deflector		12 piers			Was not built
47	Maranhão II	I	None	None					
48	Silves	V	At crown of bend	below deflector		3 piers			
49	Montagril	V	At downstream end of bend	after deflector		4 piers			

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TABLE A-2 (Continued)

STRUCTURAL AND OPERATIONAL CHARACTERISTICS
OF EXISTING SHAFT SPILLWAYS OF TABLE A-1

Index No.	Spillway		Auxiliary Structural Elements				Prototype Observations		Remarks
	Name	Type*	Deflector	Air Vent	Inlet	Anti-Vortex Arrangement	Vibration	Noise	
50	Campilhas	V	At downstream end of bend	after deflector	Ungated	None	None	None	Prototype inspected at Q = 1,890 cfs.
	International								
51	Sulak	V	None	Along shaft	Gated	12 piers and tainter gates			
52	Phumiphol	I							
53	Dez No. 2	V	None	At crest	Ungated	None			
54	Dez No. 1	V	None	At crest	Ungated	None			
55	Mibora	I			Gated				
56	San Esteban	I	None	At bend	Gated		None	None	
57	Menjil	V	None	None	Ungated	None			
58	Geehi	I			Ungated				
59	Jubilee	I	None	Along Inclined shaft	Ungated	Curtain Wall	None	None	Prototype inspected at moderate discharge
60	Ben Metir	V	At upstream end of conduit	None	Gated	6 piers			
61	Narugo	I	At inclined conduit	None	Gated	6 piers			
62	Shing Mun	V	None	None	Ungated	None			
63	Dokan	V	None	At throat of shaft	Ungated	None			
64	Sion	V							
65	Maraetal	I							
66	Jirkov	V	None	None	Ungated	None			
67	Ebenezer	V	None	None	Gated	4 piers and ring gate			
68	Alakır	V	At throat	None	Ungated	vanes			to be Model tested

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TABLE A-2 (Continued)

STRUCTURAL AND OPERATIONAL CHARACTERISTICS
OF EXISTING SHAFT SPILLWAYS OF TABLE A-1

Index No.	Spillway		Auxiliary Structural Elements				Prototype Observations		Remarks
	Name	Type*	Deflector	Air Vent	Inlet	Anti-Vortex Arrangement	Vibration	Noise	
69	San Roque	V	None	At bend	Ungated	None	None	None	Prototype inspected at Q = 920 cfs.
70	Fassideri	V	None	None	Ungated	12 piers			
71	Ladybower	V	None	None	Ungated	12 piers	None	None	Prototype inspected at Q = 2,310 cfs.
72	Mareges	I	None		Gated				
73	Sainte-Cecile d'Andorge	V							
74	Regadera	V	None	None	Ungated	8 piers	None	None	Prototype inspected at Q = 5,670 cfs.
75	Burnhope	V	None	None	Ungated	Curtain Wall and 2 fins	None	None	Prototype inspected at Q = 1,440 cfs.
76	Castillon	I			Gated				
77	Hracholuskey	V	None	None	Ungated	6 rib vanes			
78	Taf Fechon	V	None	None	Ungated	4 fins 9-in. wide	None	None	
79	Manuherikia	V	None	None	Ungated	6 piers	None	None	Prototype inspected at Q = 5,000 cfs.
80	Akongtein	V	None	None	Ungated	4 piers	None	None	Prototype inspected at Q = 1,000 cfs.
81	Stratwaich	V							
82	Pontian Ketchil	V	None	None	Ungated	15 piers	None	None	
83	Silent Valley	V	None	None	Ungated	15 fins 9-in. wide	None	None	
84	San Dalmazzo	V							
85	Canal Boissons	V							
86	Tenda	V							
87	Blacton	V							

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TABLE A-2 (Concluded)

STRUCTURAL AND OPERATIONAL CHARACTERISTICS
OF EXISTING SHAFT SPILLWAYS OF TABLE A-1

Index No.	Spillway		Auxiliary Structural Elements				Prototype Observations		Remarks
	Name	Type*	Deflector	Air Vent	Inlet	Anti-Vortex Arrangement	Vibration	Noise	
88	Front	V							
89	Galloway	V							
90	Svihov	V	None	None	Ungated	None			
91	Krauset Bauden	V							
92	Konigreich Walder	V							
93	Bojkovice	V			Ungated				
94	Lumot	V					None	None	Prototype inspected at Q = 690 cfs.
95	L'oued Sorno	V							
96	Aldeadavila	V							

* V - Vertical Shaft

I - Inclined Shaft

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TABLE A-3

HYDRAULIC CHARACTERISTICS OF EXISTING SHAFT SPILLWAYS OF TABLE A-1

Index No.	Spillway	Type	Inlet H/D_{cr}	Bend r/B	Horizontal Conduit V	d/D_c	A/A_c	F	Flow Conditions at Inlet Crest	Remarks on F and A/A_c
	U.S.B.R.-USA									
1	Hoover	I	-	4.50	134.7	0.90	0.94	3.52	Weir	model
2	Glen Canyon	I	-	8.55	163.1	0.63	0.66	6.10	Weir	model
3	Hungry Horse	I	0.264	4.90	155.2	0.68	0.72	7.10	submerged at Q = 5200 cfs	model
4	Yellowtail	I	-	9.05	137.5	0.76	0.81	4.90	Weir	model
5	Flaming Gorge	I	-	11.10	123.0	0.86	0.91	5.10	Weir	computed
6	Trinity	I	0.323	7.50	125.0	0.59	0.61	7.10	submerged at Q = 22000 cfs	model
7	Owyhee	V	0.200	2.22	115.0	0.62	0.65	5.90	Weir	computed
8	Whiskeytown	V	0.114	5.50	96.0	0.82	0.87	3.90	submerged at Q = 28400	model
9	Monticello	V	0.216	3.22	104.0	0.71	0.76	4.27	Weir	computed
10	Palisades	I	-	4.45	94.0	0.79	0.85	3.44	Weir	computed
11	Kortes	I	-	2.50	91.0	0.73	0.78	3.52	Weir	computed
12	Seminoe	I	-	3.00	97.0	0.89	0.94	3.00	Weir	computed
13	Horse Mesa	I	-	2.84		1.0	1.0		Weir	computed
14	Joes Valley	I	0.345	4.61	77.0	0.49	0.49	6.06	submerged at Q = 4500	computed
15	Gibson	V	0.218	2.00	88.5	0.77	0.82	3.28	Weir	computed
16	Spangler	V	0.260	2.27	69.0	0.59	0.56	4.40		computed
17	Little Panoche	V	0.965	2.67	50.0	0.56	0.57	4.10	submerged	computed
18	Hearte Butte	V	1.650	1.91	60.0	0.59	0.61	4.00	submerged at Q = 3000 cfs	computed
19	Guernsey	V	0.136	0.985	64.5	0.76	0.82	2.64	Weir	computed
20	San Luis	V	0.0596	2.00	22.0	0.55	0.56	1.92	Weir	model
21	Shade Hill	V	1.270	1.04	59.0	0.50	0.50	4.00	submerged at Q = 3500 cfs	Prototype
22	Arbuckle	V	1.300	1.32	54.0	0.82	0.875	3.30		computed
23	Foss	V	1.000	1.32	52.0	0.80	0.86	3.20	submerged at Q = 2200 cfs	computed

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TABLE A-3 (Continued)

HYDRAULIC CHARACTERISTICS OF EXISTING SHAFT SPILLWAYS OF TABLE A-1

Index No.	Spillway	Type	Inlet	Bend	Horizontal Conduit				Flow Conditions at Inlet Crest	Remarks on F and A/A_c
			H/D_{cr}	r/B	V	d/D_c	A/A_c	F		
24	Sherman	V	0.585	1.50	53.0	0.44	0.416	5.70		computed
25	Cheney	V	0.845	2.68	51.0	0.77	0.82	3.36		computed
26	Ft. Cobb	V	0.880	1.32	50.0	0.79	0.85	3.20		computed
27	San Luis Forebay	V	0.0496	1.43	53.5	0.56	0.56	4.10	Weir	model
28	Red Willow	V	0.735	1.04	48.0	0.66	0.70	3.04		computed
29	Norman	V	0.685	1.32	48.0	0.77	0.83	3.14		computed
30	Jamestown	V	0.462	1.32	47.0	0.82	0.87	2.86	submerged	computed
	T.V.A.-USA									
31	Fontana	I	-	2.95	146.0	0.71	0.74	5.24	Weir	model
32	Watauga	V	0.101	2.20	88.0	0.70	0.75	3.34	Weir	model
33	South Holston	V	0.101	2.20	88.0	0.70	0.75	3.34	Weir	computed
	Corps of Engineers-USA									
34	Eau Galle	V	3.200	Streamlined	53.0	1.00	1.00		submerged	
35	Fort Peck	V								
36	Pleasant Hill	V								
	Others-USA									
37	Davis Bridge	V	0.100	2.44	81.5	0.82	0.87	3.40	Weir	model
38	Bouquet	V	0.312	2.00	53.0	0.58	0.60	4.75		computed
39	Kingsley	V	0.312	2.24	85.0	1.00	1.00			computed
40	San Pablo	V	0.152			1.00	1.00		Weir	model
41	Round Butte	I								
	L.N.E.C.-Portugal									
42	Paradela	V	0.129	3.20	69.5	0.78	0.84	2.72		computed
43	Miranda	I	0.248	3.90	107.0	0.60	0.63	4.95		computed
44	Pego do Altar	V	0.0825	1.20	58.0	0.63	0.66	2.40		computed
45	Pracana	V	0.410	2.10	86.5	0.83	0.83	2.90	submerged at Q = 58000 cfs	computed
46	Maranhão I	V	0.091	1.50	70.0	0.81	0.87	2.26	Weir	computed
47	Maranhão II	I	0.236	4.00	79.0	0.72	0.77	2.90	Weir	computed
48	Silves	V	0.142	1.61	56.5	0.80	0.86	2.08	Weir	computed

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TABLE A-3 (Continued)

HYDRAULIC CHARACTERISTICS OF EXISTING SHAFT SPILLWAYS OF TABLE A-1

Index No.	Spillway		Inlet	Bend	Horizontal Conduit				Flow Conditions at Inlet Crest	Remarks on F and A/A_c
	Spillway	Type	H/D_{cr}	r/B	V	d/D_c	A/A_c	F		
49	Montagril	V	0.187	1.22	57.0	0.80	0.86	2.10	submerged at Q = 2280 cfs	computed
50	Campilhas	V	0.397	2.00	39.0	0.85	0.90	1.71	submerged at Q = 4250 cfs	computed
	International									
51	Sulak	V	0.0615	1.64	75-98	0.60	0.63	4.06-3.10	Weir	model
52	Phumiphol	I	-		123.0	0.74	0.79	4.22		computed
53	Dez No. 2	V	-	1.50	140.0	0.55	0.56	5.75	Weir	computed
54	Dez No. 1	V	-	1.50	121.0	0.52	0.53	4.80	Weir	computed
55	Mibora	I	-		122.0	0.65	0.68	5.0	Weir	computed
56	San Esteban	I	-		116.0	0.32	0.28	8.0		computed
57	Menjil	V	0.120	2.88	182.0	1.0	1.0		Weir	computed
58	Geehi	I	0.124		110.0	0.71	0.75	4.50		computed
59	Jubilee	I	0.108	1.80		1.00	1.00		Weir	computed
60	Ben Metir	V	1.400		97.0	0.70	0.74	4.80	submerged at Q = 19000 cfs	computed
61	Narugo	I	-	6.64					Weir	
62	Shing Mum	V		2.00	77.0	1.00	1.00		Weir	model
63	Dokan	V	0.124	0.50	72.0	1.00	1.00		Weir	model
64	Sion	V								
65	Maraetai	I	-		87.0	0.66	0.70	4.00		
66	Jirkov	V	0.120		80.0	0.43	0.40	8.00		computed
67	Ebenezer	V	0.167	2.50	79.0	0.82	0.82	3.72	Weir	computed
68	Alakır	V	2.780	2.25	41.6	0.58	0.60	2.61	submerged at Q = 2640 cfs	computed
69	San Roque	V	0.378	2.50	75.0	1.00	1.00		submerged	model
70	Fassideri	V	0.050	2.61	60.0	1.00	1.00		Weir	model
71	Ladybower	V	0.0815	2.33	63.0	0.93	0.97	3.20	Weir	computed
72	Marèges	I	-						Weir	
73	Sainte-Cecile d' Andorge	V								
74	Regadera	V	0.164	0.50	64.0	0.68	0.72	3.20		computed
75	Burnhope	V	0.054	1.33	60.0	0.41	0.38	5.50	Weir	computed

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TABLE A-3 (Concluded)

HYDRAULIC CHARACTERISTICS OF EXISTING SHAFT SPILLWAYS OF TABLE A-1

Index No.	Spillway		Inlet	Bend	Horizontal Conduit				Flow Conditions at Inlet Crest	Remarks on F and A/A_c
	Spillway	Type	H/D_{cr}	r/B	V	d/D_c	A/A_c	F		
76	Castillon	I	-						Weir	
77	Hracholuskey	V	0.194		62.0	0.46	0.45	4.10		computed
78	Taf Fechon	V	0.0425	0.94	59.0	0.41	0.38	5.20	Weir	computed
79	Manuherikia	V	0.059	1.50	66.0	1.00	1.00		Weir	computed
80	Akongtein	V	0.192	3.30	55.0	0.72	0.78	3.80	submerged at Q = 1600 cfs	computed
81	Stratwaich	V								
82	Pontian Ketchil	V	0.054	0.77	45.0	0.46	0.45	3.72	Weir	computed
83	Silent Valley	V	0.0288	1.125	43.0	0.33	0.29	3.90	Weir	computed
84	San Dalmazzo	V								
85	Canal Boissons	V	0.0985							
86	Tenda	V								
87	Blacton	V								
88	Front	V								
89	Galloway	V	0.118							
90	Švihov	V								
91	Krauset Bauden	V								
92	Konigreich Walder	V								
93	Bojkovice	V								
94	Lumot	V								
95	L'oued Sorno	V								
96	Aldeadavila	V								

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APPENDIX B

COMPUTATIONS

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APPENDIX B-1

AIR DISCHARGE FROM THE OUTLET PORTAL

A simplified velocity distribution of the air layer above the water surface is considered as shown by the dashed line in Figure B-1. The discharge of the air and the velocity of the inflowing air can be computed, using the pressure data, as follows:

1. The inflowing air discharge equals the outflowing air discharge.

$$Q_a \text{ in} = Q_a \text{ out}$$

or
$$V_a \text{ in } (B-d-y)\ B = \frac{V_a \text{ out } y \cdot B}{2} \qquad (B1)$$

in which V_a out, B, and d are known. Assume V_a out = V water. The values V_a in and y are unknown.

2. Assume a value for y and compute Q_a out.

3. Compute V_a in from Equation B1.

4. Compute the equivalent diameter of the inflowing air layer section.

$$D_e = 4 \frac{A_a}{P} \qquad (B2)$$

in which: A_a = cross-sectional area of the inflowing air layer

P = wetted perimeter at an inflowing air layer section

5. Compute Reynolds number for the inflowing air.

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$$R_e = \frac{V_a \text{ in } D_e}{\nu}$$

6. Find Darcy-Weisbach friction coefficient, f, from Moody-diagram.

7. Compute friction loss coefficient, K_f,

$$K_f = \frac{fL}{D_e}$$

in which L is the length of conduit.

8. Compute total loss coefficient, K.

$$K = K_f + K \text{ entrance} + K_v$$

in which: K entrance = entrance loss coefficient = 0.5

K_v = velocity head coefficient = 1.0

9. Compute V_a in from,

$$V_{a \text{ in}} = \sqrt{\frac{2g\, p_a}{K}} \qquad \text{(B3)}$$

in which: p_a = measured pressure at roof of conduit

10. Check if $V_{a \text{ in}}$ as found in steps 3 and 9 are equal. If not, then assume another value for y in step 2 and repeat steps 3 to 9, inclusive.

11. The maximum velocity of the inflowing air is 1.5 times the average velocity.

The results of the air discharge and of the air velocity are shown in Table B-1.

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TABLE B-1

AIR DISCHARGE FROM THE OUTLET PORTAL

AT INCIPIENT-SEALING CONDITIONS

r/B	t/B	A/A_c	F	Q cfs	p_a ft. air	y ft	AVG. V_a fps	Q_a cfs	MAX. V_a fps	V WATER fps
0.5	0.0	0.535	7.75	1.26	9.60	0.095	14.9	0.298	22.2	18.6
1.5	1/64	0.78	4.04	1.01	4.23	0.043	8.0	0.08	12.0	11.67
1.5	1/16	0.72	5.52	1.22	5.95	0.053	10.0	0.133	15.0	15.3
1.5	1/8	0.705	5.66	1.21	5.74	0.050	10.0	0.129	15.0	15.1
2.5	1/64	0.835	3.88	1.08	4.78	0.030	8.0	0.0625	12.0	11.63
2.5	1/16	0.806	4.35	1.15	4.58	0.035	8.2	0.0765	12.3	12.81
2.5	1/8	0.753	4.41	1.05	5.60	0.05	9.2	0.10	13.8	12.53

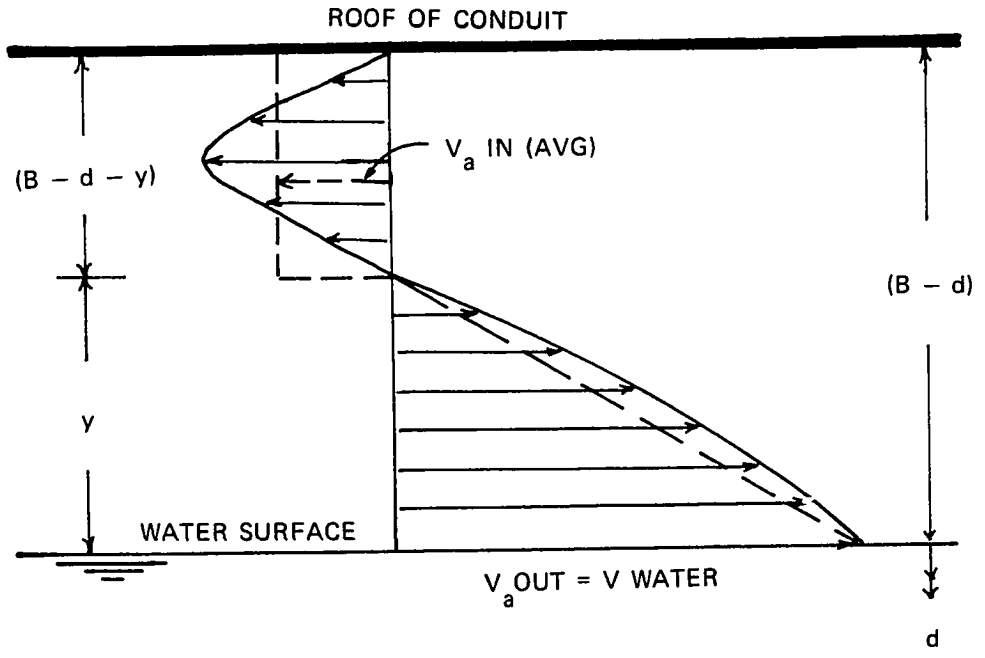

Figure B-1 Schematic Diagram of the Velocity Distribution of the Air Layer

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VITA

Yusuf G. Mussalli was born in Aleppo, Syria on February 2, 1939. He attended Aleppo College, an American missionary school, and graduated in June 1957. He graduated from Robert College, the American College of Istanbul, with a Bachelor of Science in Civil Engineering in July 1960. He worked with the Euphrates Project Authority in Syria from September 1960 to February 1963 and attended a seminar on irrigation and drainage in the summer of 1961 organized by the U.N. Food and Agriculture Organization in the Soviet Union. In February 1963 he joined the Middle East Technical University, Ankara, Turkey and graduated in December 1964 with a Master of Science in Civil Engineering. He worked with the Delft Hydraulics Laboratory, the Netherlands, from January 1965 to September 1965 as a civil engineer. He was placed at the Georgia Institute of Technology by the American Friends of the Middle East where he attended the Graduate Division from September 1965 to the present. He was awarded a Master of Science in Civil Engineering in June 1967. While at the Georgia Institute of Technology he was employed by the School of Civil Engineering as a graduate research assistant. During the summer of 1967 he worked for the U.S. Army Corps of Engineers, Sacramento, California as a hydraulic engineer.

At Georgia Tech, Mr. Mussalli was chosen as an Outstanding Middle Eastern Student in the U.S.A. in 1967 and as the Outstanding International Student at Georgia Tech in 1969. He was the president of the Organization of Arab Students at Georgia Tech, the vice president of the International

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Student Organization in 1967, the vice president of the Episcopal Church on Campus in 1968. He is a member of the American Friends of the Middle East, an associate member of the American Society of Civil Engineers, a member of Chi Epsilon honorary civil engineering fraternity, a member of Sigma Xi research society, a member of the International Association for Hydraulic Research, and a member of the Water Pollution Control Federation.

He is single.

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