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# Closed Conduit to Open Channel USU Stilling Basin

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# CLOSED CONDUIT TO OPEN CHANNEL

# USU STILLING BASIN

ABSTRACT: Criterion have been developed for designing a stilling basin to serve as a transition from closed conduit flow to open channel flow for a fully submerged pipe outlet. The unique feature of the stilling basin is the short-pipe energy dissipator so located and designed as to provide maximum energy dissipation for the basin configuration. The expanding characteristics of a submerged jet were used in establishing the length of the stilling basin. The unsteadiness of the water surface and the relative boil height in the model basin were used as the criteria for evaluating the effectiveness of the structure for energy dissipation. Relations between the tailwater depth, the outlet flume floor elevation, the height of boils in the stilling basin, the width of the stilling basin, and the amount of freeboard have been studied. The interrelationships among these variables have been shown graphically.

KEYWORDS: closed conduit flow; design; energy dissipation; hydraulics, models, open channel flow; stilling basins.

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# CLOSED CONDUIT TO OPEN CHANNEL

# USU STILLING BASIN

By Gordon H. Flammer,[1] M. ASCE, Gaylord V. Skogerboe,[2] M. ASCE,
Chi-Yuan Wei,[3] and Hameed Rasheed[4]

## INTRODUCTION

To prevent possible erosion below overflow spillways, chutes, sluices, and pipe outlets, the excess kinetic energy needs to be dissipated in either a vertical or horizontal direction, or both. Horizontally, the energy may be dissipated by shear drag, pressure drag, or an increase in piezometric head. Vertically, it may be dissipated by diffusion of jets vertically upward or downward.

The energy dissipator under study (Fig. 1) is designed as a transition from pipe flow to open channel flow. Energy is dissipated in both the vertical and horizontal directions with shear drag, pressure drag, and vertical diffusion as the major dissipation mechanisms.

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Energy dissipation is a common problem in the design of hydraulic structures. The mechanisms of dissipation are so complicated that it is almost invariably necessary to run laboratory studies on any proposed design using model theory. For large structures, model studies are usually economically justified to test any unique energy dissipator design. For small structures economics do not justify such studies so that generalized designs have been studied in order to meet a wider range of conditions.

Typical examples of generalized closed conduit to open channel stilling basins are the Contra Costa energy dissipator, the USBR impact stilling basin VI, and the manifold stilling basin. The Contra Costa energy dissipator (Fig. 2a) was developed in 1956 at the Fluid Mechanics Laboratory of the University of California, Berkeley (1). The dissipator is for use in the reestablishment of natural channel flow conditions at culvert outfalls which have uncontrolled, excessively high, effluent velocities at depths of less than half the culvert diameter.

The impact stilling basin VI (Fig. 2b) was developed by the U.S. Bureau of Reclamation (2, 3, and 4) to meet the need for relatively small basins which could provide energy dissipation relatively independent of tailwater variation. This basin is recommended for entering velocities of less than 30 fps. The efficiency of this energy-dissipator is greater than the efficiency of the hydraulic jump for the same Froude number. The obstructing baffle is designed so the flow striking it is deflected upstream and toward the basin floor. Tailwater as high as $d \div g/2$ does improve the performance somewhat by reducing outlet velocities, providing a smoother water surface, and reducing tendencies toward erosion. A protective blanket of riprap downstream from the structure is suggested as a safeguard against erosion.

A model study of a manifold stilling basin was conducted in the Hydraulic Laboratory at Colorado State University (5). The general layout of this basin is shown in Fig. 2c. The width and length of the model were kept constant at 1 and 8 feet, respectively. The depth was varied from one foot at the inlet to zero at the downstream end of the model. A practical design was developed and the necessary field design criteria specified.

## DIMENSIONAL ANALYSIS

The flow pattern in the USU stilling basin will depend upon the variables Q, g, $D_1$, $D_2$, $Y_1$, $Y_2$, $y_b$, $y_t$, L, $L_b$, W, and $W_b$ (Fig. 1), where $D_1$ is the diameter of the inlet pipe, $D_2$ is the diameter of the dissipator pipe, $Y_1$ is the height of the inlet pipe above the bottom of the stilling basin, $Y_2$ is the distance between the centerline of the inlet pipe and the floor of the outlet flume, $y_b$ is the height of water in the basin above the centerline of the inlet pipe, $y_t$ is the depth of the tailwater in the open channel, L is the length of the dissipator pipe, $L_b$ is the length of the stilling basin, W is the width of the slot of the short-pipe energy dissipator, and $W_b$ is the width of the stilling basin. These variables can be related by the use of dimensional analysis. The dimensional matrix appears as

$$\begin{array}{c|cccccccccccc} & Q & g & D_1 & D_2 & Y_1 & Y_2 & y_b & y_t & L & L_b & W & W_b \\ \hline L & 3 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ T & -1 & -2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}$$

The discharge is allowed to appear in only one dimensionless parameter, and the diameter of the inlet pipe ($D_1$) is selected as a repeating variable. Dimensional analysis, using $D_1$ as a repeating variable, yields the following functional relationship.

$$f\left(\frac{Q^2}{gD_1^5}, \frac{D_2}{D_1}, \frac{Y_1}{D_1}, \frac{Y_2}{D_1}, \frac{y_b}{D_1}, \frac{y_t}{D_1}, \frac{L}{D_1}, \frac{L_b}{D_1}, \frac{W}{D_1}, \frac{Wb}{D_1}\right) = 0. \quad . \quad (1)$$

or

$$\frac{Q^2}{gD_1^5} = f\left(\frac{\lambda}{D_1}\right) \quad \cdots\cdots\cdots\cdots \quad (2)$$

Where $\lambda$ is any length dimension.

Viscosity is ignored in the above analysis because its relative importance is analytically indeterminate due to the complexity of the viscous shear process. Therefore, several model sizes were tested to evaluate any scale effect resulting from ignoring viscosity or any other pertinent variables.

## DISSIPATOR PIPE

The relative dissipator pipe dimensions are undoubtedly critical in determining the energy dissipation characteristics of the basin. Rasheed (6) suggested the following design ratios: $D_2/D_1 = 1.85$; $L/D_1 = 1.0$; and $W/D_1 = 0.5$. A comprehensive study of the design of the dissipator pipe was undertaken in order to extend Rasheed's range of results.

### Equipment

The initial model consisted of a 3-1/4 inch diameter inlet pipe ($D_1$) connected to a box-like stilling basin, 18 inches wide and 10 inches long. The stilling basin was connected to a rectangular flume having the same width as the stilling basin. A tail gate located at the downstream end of the flume was used to evaluate the effect of tailwater depth. An elbow meter was used to measure the flow rate. A short-pipe energy dissipator was placed on the wall of the basin opposite the incoming submerged jet (Fig. 1).

## Experiments

In the design of the short-pipe energy dissipator, the variables involved are the diameter of the dissipator pipe ($D_2$), the length of the dissipator pipe (L), and the slit width, (W). In order to see how each of these variables affect the overall performance of the stilling basin, one of the three dimensions was varied while the other two were kept fixed. At the same time, the geometry of the stilling basin was fixed.

First of all, the slit-width ratio ($W/D_1$) was varied without changing the remaining dimensions. This was done by fixing the dimensions $D_1$ = 3-1/4 inches, $D_2$ = 6-1/2 inches, $L_b$ = 10 inches, L = 3-1/8 inches, $Y_1$ = 4-3/4 inches, and width of open channel, b = 20 inches. The W/D ratios, 0.310, 0.460, 0.615, 0.770, 0.924, and 1.000 were tested. The fluctuations of the water surface in the stilling basin were sensed by a sonic wave transducer and recorded on an x-t recorder. On the basis of these fluctuations and the basin boil height, the ratio yielding the best hydraulic performance was determined as 0.46, say 0.5.

To determine the optimum dissipator pipe length ratio ($L/D_1$), the ratios 0.90, 1.10, 1.15, and 1.39 were tested. The dimensions $D_1$ = 3-1/4 inches, $D_2$ = 6-1/2 inches, W = 1-1/2 inches, and $Y_1$ = 4-3/4 inches were fixed. The best results, using the fluctuations of the water surface and boil heights as criteria were obtained at ratios in the vicinity of 1.0

Under normal circumstances, the expansion ratio in the region of expansion of a submerged jet is approximately 1:5 (7,8). Since the length of the stilling box is 10 inches and the incoming jet has a diameter of 3-1/4 inches, the diameter of the expanding jet will be approximately 6 inches when it reaches the short-pipe energy dissipator. Accordingly, a dissipator pipe size was chosen large enough to insure enclosing the entire jet, i.e. 6-1/2 inches diameter. Thus, a diameter ratio, $D_2/D_1$, of 2.0 was selected and then verified experimentally.

## STILLING BASIN

### Model basin

The second phase of this study was concerned with optimizing the design of the stilling basin structure (9) using the above recommended dimensionless ratios for the dissipator pipe. To facilitate this phase of the study, a steel box was fabricated having a height of 6 feet, a length of 4 feet, and a width of 4 feet. Steel guides were welded on the inside of the steel box to form vertical and horizontal rows of guides to facilitate changing the dimensions of the stilling basin by using false walls and a false floor inside the steel box. A wooden flume, 22 inches wide, 6 feet long, and 20 inches high served as the outflow channel for the stilling basin structure. Fig. 3 shows the dimensions of the model stilling basin, while pictures of the model structure are shown in Fig. 4.

As indicated, the height of the floor of the flume and the width and length of the stilling basin were easily adjusted. The length of the basin was adjustable from 6-1/2 to 24 inches, the width from 14 to 48 inches, and the height from 9-3/4 to 37 inches. Three inlet pipes with inside diameters of 3-1/4, 6, and 10 inches were used in the study. Initial tests used the 3-1/4 inch inlet pipe. A 12-inch Parshall flume located downstream from the model stilling basin was used to measure the flow rate.

### Experimental design

The range of discharges chosen was from 0.48 to 1.33 cfs for the 3-1/4 inch diameter inlet pipe. The discharge limits were determined by the maximum discharge available for the largest inlet pipe used (10 inches) and the minimum discharge at which an energy dissipation structure might be needed. These two discharges were tested for the 3-1/4 inch inlet pipe, along with an intermediate discharge of 0.80 cfs. The corresponding discharges used for the 6 and 10 inch diameter inlet pipes were determined from the dimensionless ratio $Q^2/gD_1^5$.

Each test was conducted maintaining $D_2/D_1 = 2.0$, $L/D_1 = 1.0$, $W/D_1 = 0.5$, and $Y_1/D_1 = 1.5$. The remaining dimensionless ratios, $W_b/D_1$, $L_b/D_1$, and $Y_2/D_1$ were systematically varied throughout the testing program. In addition to varying $W_b$, $L_b$, and $Y_2$, the inlet diameter, $D_1$, was also varied in order to evaluate scale effects. For each physical condition, the hydraulic performance was observed using three discharges. For each discharge, the tailwater depth (ratio $y_t/D_1$) was varied over as large a range as possible.

Width of stilling basin

Width ratios ($W_b/D_1$) of 4.0 and 6.77 were tested. At a discharge of 0.48 cfs and an inlet diameter of 3.25 inches, the Froude number ($F_1$ defined as $V_1/\sqrt{gD_1}$) was 2.8. The tailwater depth, $y_t/D_1$, was set at 1.54. Observations were also made at $F_1 = 4.7$ and $F_1 = 7.7$. It appeared that $W_b/D_1 = 6.77$ resulted in a better hydraulic performance in the stilling basin than $W_b/D_1 = 4.0$. The greater basin width increased the flow path in the lateral direction.

The effect of stilling basin width was dependent upon $F_1$ and $(Y_2 + y_t)/D_1$. The relationship between width and these ratios is shown later (Fig. 6).

There was some question as to the best choice of the length for the Froude number. Initially, the Froude number was defined as $V_1/\sqrt{gy_b}$. A plot of the relative boil height, $[y_b - (Y_2 + y_t)]/D_1$, against $V_1/\sqrt{gy_b}$ shows a reasonably consistant relationship of

$$[y_b - (Y_2 + y_t)]/D_1 = 0.175 \left(V_1/\sqrt{gy_b}\right)^{1.73} \quad \ldots\ldots\ldots\ldots (3)$$

This expression is essentially independent of the relative widths or relative depths of the stilling basin for the ranges studied. On the other hand, when the relative boil height was plotted against $V_1/\sqrt{gD_1}$, the effect of the relative width and relative depth were readily evident--as will be shown later. Therefore, the latter so-called Froude number was chosen for design purposes.

## Length of stilling basin

The stilling basin length ratio ($L_b/D_1$) is a function of the diameter ratio ($D_2/D_1$) because of the expanding characteristics of a submerged jet. If the expansion ratio of the nominal boundary of the jet is assumed to be 1:5, then in order for the jet to expand to $D_2$, the length ratio is related to the diameter ratio by the following equation:

$$L_b/D_1 = 2.5\ (D_2/D_1 - 1) + 1.0 \qquad (4)$$

If the length ratio is obtained by Eq. 4, the depth of tailwater required to achieve a desired degree of energy dissipation, as evidenced by the relative boil height, is primarily a function of the Froude number ($F_1$). For the selected diameter ratio of 2.0, the stilling basin length ratio becomes 3.5.

## Tailwater elevation

The tailwater elevation has a pronounced effect on energy dissipation in the stilling basin. It is the sum of the bed elevation above the centerline of the pipe, $Y_2$, and the flow depth, $y_t$, in the outlet flume. To evaluate the effect of flume floor elevation, a 6-inch inlet pipe was installed and the following dimensionless ratios were used in initial tests:

$D_2/D_1 = 2.0$, $L/D_1 = 1.0$, $W/D_1 = 0.5$, $Y_1/D_1 = 1.5$, $W_b/D_1 = 4.0$ and $L_b/D_1 = 2.0$. The $Y_2/D_1$ ratio was varied from 1.50 to 3.00 for $F_1 = 3.5$ ($Q = 2.73$ cfs). As $Y_2/D_1$ was increased, the difference between water surface elevations in the basin and the tailwater surface in the flume were reduced, as would be expected. Then, maintaining $Y_2/D_1 = 1.50$ for the 3.25-inch inlet pipe at a Froude number of 4.70, flow conditions at different tailwater depths were observed as shown in Fig. 5.

To evaluate the relation between tailwater depth ratio, $y_t/D_1$, and outlet flume floor elevation ratio, $Y_2/D_1$, the heights of the boils in the basin above the pipe centerline were recorded, and denoted by $y_b$. The elevation difference between the top of the boil and the surface of the open channel flow, which is defined in dimensionless terms by $\Delta = \left[y_b - (Y_2 + y_t)\right]/D_1$, is a function of $m = (Y_2 + y_t)/D_1$. The relationship between $\Delta$, m, and $F_1$ is shown in Fig. 6.

## DESIGN

In a practical situation, the discharge (Q) will be given, the inlet pipe diameter ($D_1$) will usually be determined by economics, and the tailwater depth ($y_t$) will be determined by downstream conditions. With these values given, a desired boil height can be realized by the choice of $Y_2$ and $W_b$ using Fig. 6. The best combination of these two dimensions is based on economics. A suitable freeboard above the boil is chosen--it appears that 1/2-foot steps would be practical with 1/2-foot freeboard being an absolute minimum. Recommended freeboard ratios ($f_b/D_1$) can be obtained from Fig. 6.

A practical design problem might be as follows:

Given: Q = 200 cfs, $D_1 = 3$ feet; $y_t = 5$ feet

Then: $\frac{D_2}{D_1} = 2.0$, $\frac{L}{D_1} = 1.0$, $\frac{W}{D_1} = 0.5$, $\frac{Y_1}{D_1} = 1.5$, and $\frac{L_b}{D_1} = 3.5$

Since: $\frac{V_1}{\sqrt{gD}} = 2.9$

From Fig. 6, for m = 3.0: $Y_2 = 4$ ft., $W_b = 12$ ft., $y_b = 10.5$ ft., boil height = 0.5 ft., $f_b = 0.5$ ft., or the overall size of the basin would be 12 ft. wide X 10.5 feet long X 15.5 feet deep.

From Fig. 6, for m = 4.0: $Y_2 = 7$ feet, $W_b = 10.5$ feet, $y_b = 13.2$ feet, boil height = 0.4 feet, $f_b = 0.5$ feet, or the overall size of the basin would be 10.5 feet wide X 10.5 feet long X 18.2 feet deep.

## SUMMARY

Criterion have been developed in this study for designing a stilling basin to serve as a transition from closed conduit flow to open channel flow.

The introduction of a short-pipe energy dissipator in the stilling basin has proven effective in dissipating energy. The energy is dissipated mainly by shear drag, pressure drag, and the diffusion action of the submerged jet in the stilling basin. The unsteadiness, or smoothness, of the water surface as well as the relative boil height in the model basin were used as the criterion for evaluation of the effectiveness of the structure for energy dissipation.

Optimum dissipator pipe dimensions were first determined by holding the stilling basin dimensions fixed. Then, using these recommended dissipation pipe ratios, the stilling basin dimensions were varied in order to optimize the design of the stilling basin structure.

The stilling basin was designed for a fully submerged pipe outlet. The flow pipe and the dissipator pipe were designed to be located on the same centerline, at $Y_1/D_1 = 1.5$ above the stilling basin floor. The optimum dissipator pipe ratios were found to be $W/D_1 = 0.5$, $D_2/D_1 = 2.0$, and $L/D_1 - 1.0$.

In the studies to optimize the design of the stilling basin structure, three diameters of inlet pipe were used in order to determine scale effects. Within the accuracy of the measurements used, no scale effects were detected.

The expanding characteristics of a submerged jet were used in establishing the length of the stilling basin. When $D_2/D_1 = 2.0$, the stilling basin length ratio becomes 3.5 ($L_b/D_1 = 3.5$).

A graphical relationship was obtained between the tailwater depth ($y_t$), the outlet flume floor elevation ($Y_2$), the height of boils in the stilling basin ($y_b$), and the width of the stilling basin ($W_b$). The boil height above the tailwater surface in the outlet open channel was found to be a function of the Froude number ($F_1$) and the relative elevation of the tailwater surface above the center line of the inflow pipe ($Y_2 + y_t$). In addition, the width of the stilling basin ($W_b$) and the amount of freeboard ($f_b$) have been related to the Froude number and the relative elevation of the tailwater surface. The interrelationships among $F_1$, $(Y_2 + y_t)/D_1$, $y_b/D_1$, $W_b/D_1$, and $f_b/D_1$, are shown in Fig. 6, which can be used for practical design.

# APPENDIX I. - REFERENCES

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# APPENDIX II - NOTATION

$b$ = width of the open channel

$D_1$ = diameter of the inlet pipe

$D_2$ = diameter of the dissipator pipe

$f_b$ = freeboard

$F_1$ = Froude number

$g$ = acceleration due to gravity

$H$ = height of stilling basin

$L$ = length of the dissipator pipe

$L_b$ = length of stilling basin

$m$ = relative tailwater depth above pipe centerline

$Q$ = discharge

$V_1$ = mean velocity in inlet pipe

$V_2$ = mean velocity in the open channel

$W$ = slot width in the dissipator pipe

$W_b$ = width of the stilling basin

$Y_1$ = elevation of the inlet pipe centerline above the bottom of the stilling basin

$Y_2$ = elevation of the open channel bed above the centerline of the inlet pipe

$y_b$ = height of the boil in the stilling basin above the centerline of the inlet pipe

$y_t$ = tailwater depth in the open channel outlet

$\Delta$ = relative boil height above tailwater

$\lambda$ = any length dimension

# CLOSED CONDUIT TO OPEN CHANNEL

# USU STILLING BASIN

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## LIST OF FIGURES

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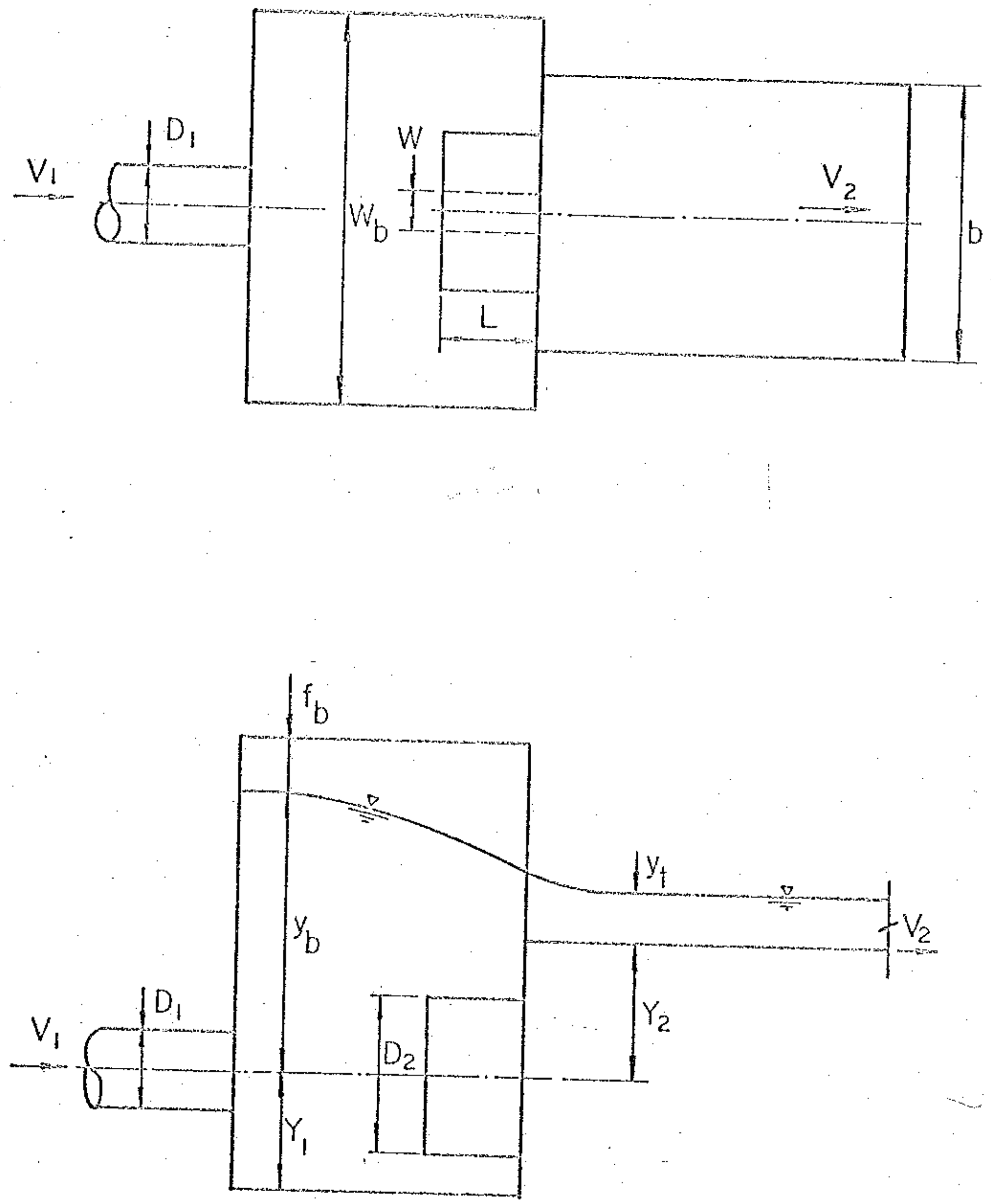
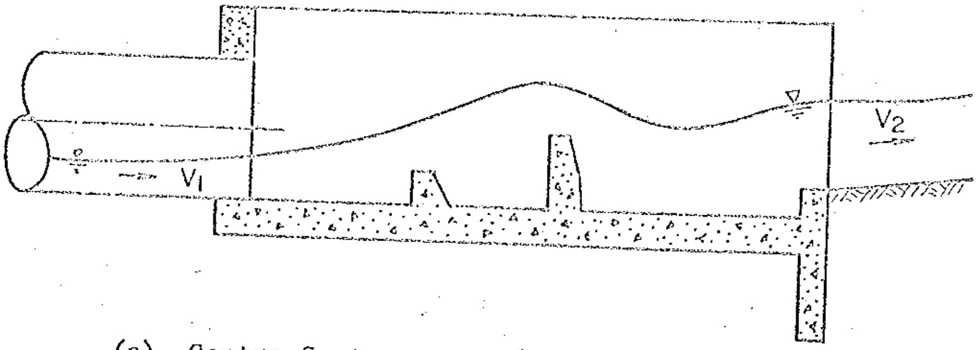
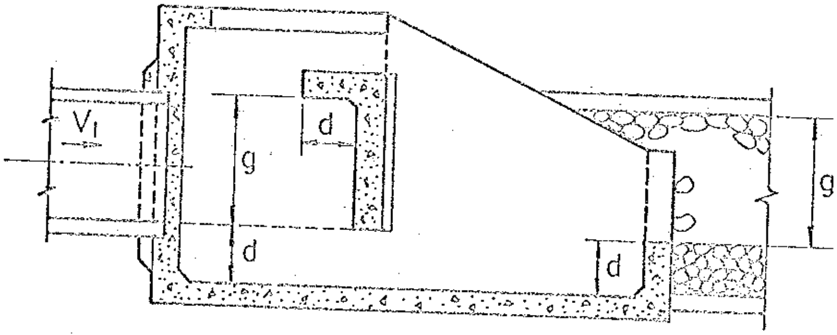


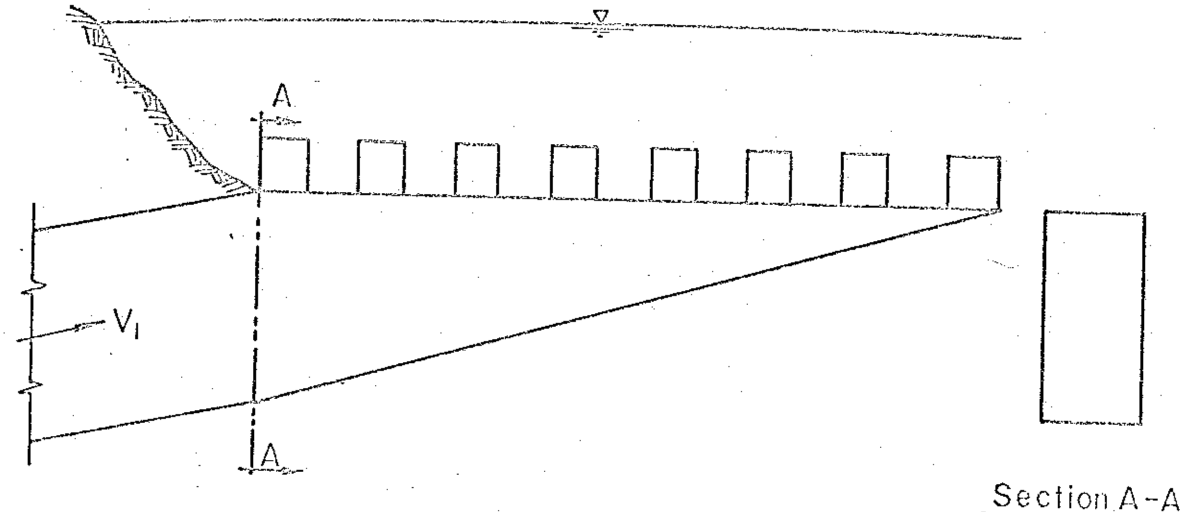
FIG. 1. - USU STILLING BASIN



(a) Contra Costa energy dissipator.

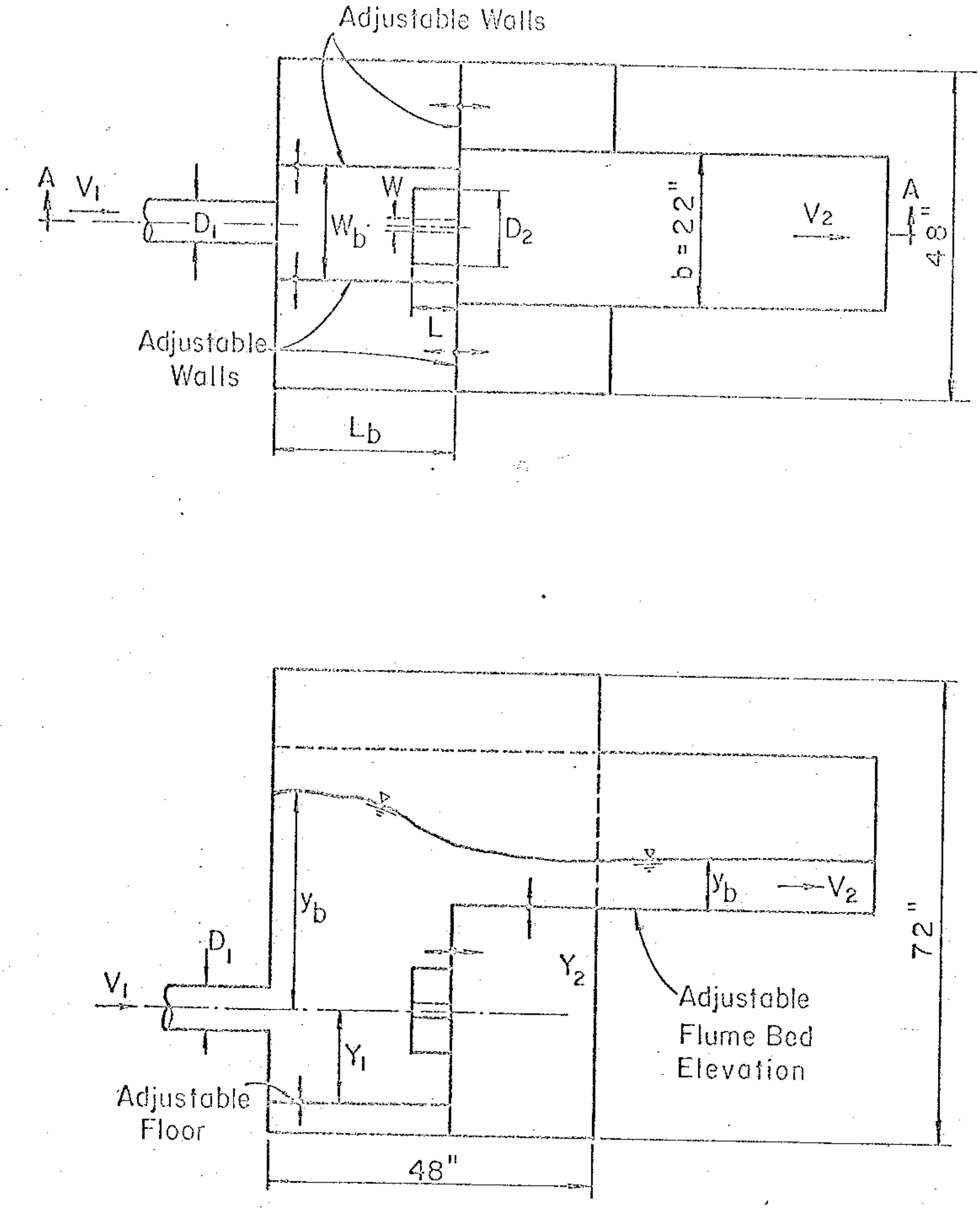


(b) USBR impact stilling basin VI.



(c) Manifold stilling basin.

FIG. 2. - EXAMPLES OF CLOSED CONDUIT TO OPEN CHANNEL STILLING BASINS



SECTION A - A

FIG. 3 - GENERAL LAYOUT OF MODEL USU STILLING BASIN

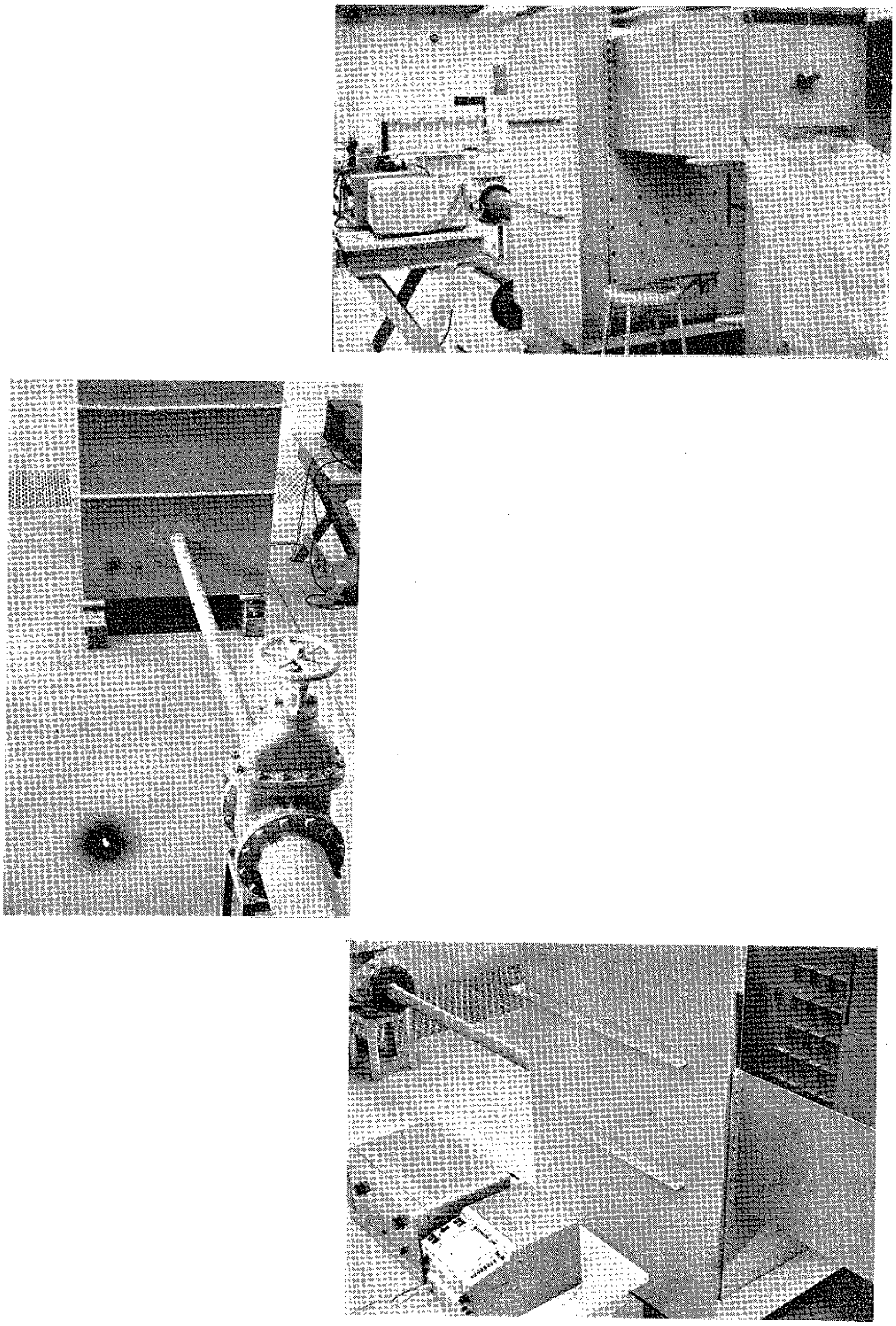
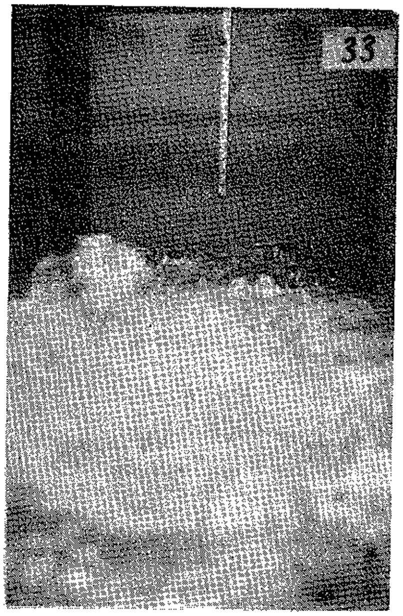
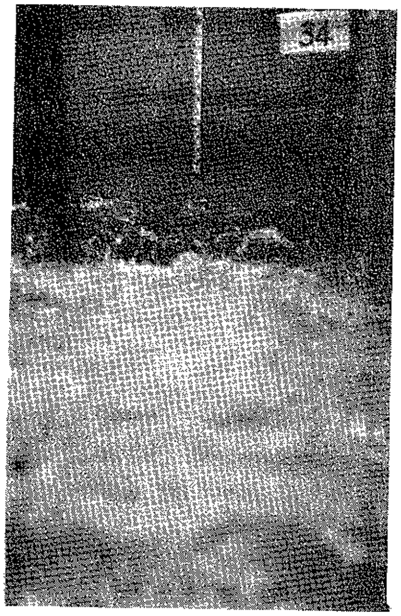


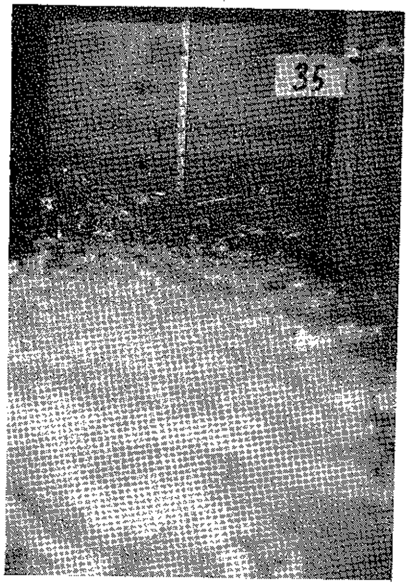
FIG. 4. - MODEL USU STILLING BASIN



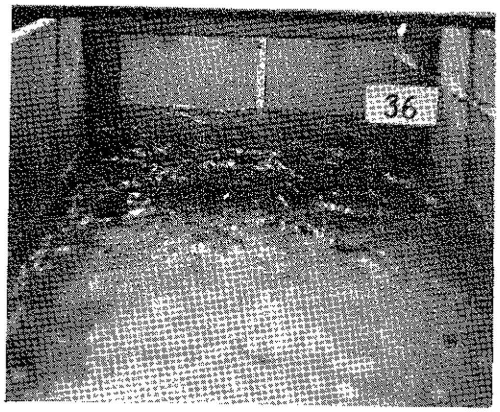
(a) $y_t/D_1 = 0.61$



(b) $y_t/D_1 = 1.54$



(c) $y_t/D_1 = 2.77$



(d) $y_t/D_1 = 4.61$

FIG. 5. - COMPARISON OF STILLING BASIN PERFORMANCE
AT DIFFERENT TAILWATER DEPTH RATIOS

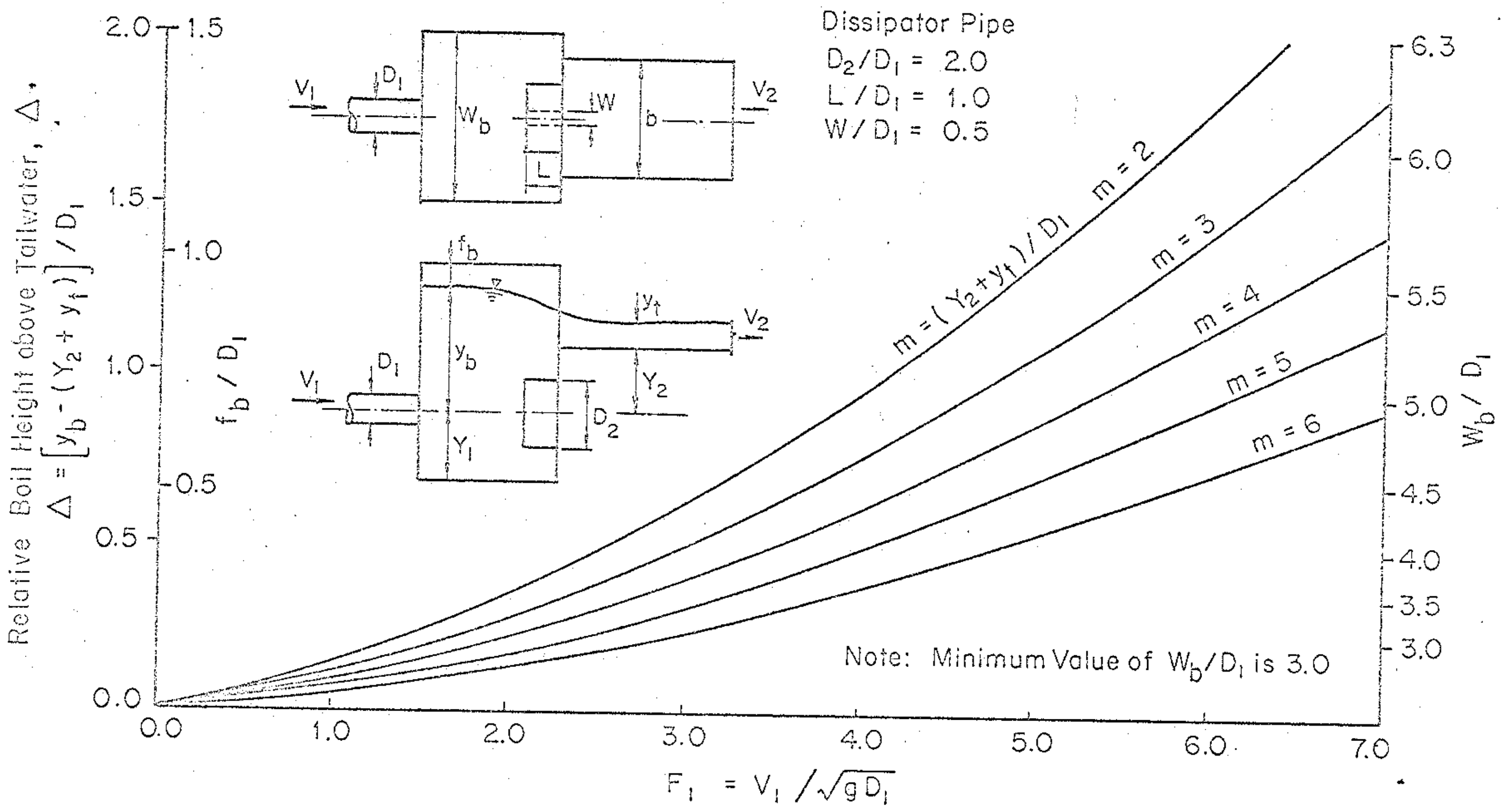


FIG. 6 - DESIGN RELATIONSHIPS FOR USU STILLING BASIN