SPILLWAY STILLING BASIN FOR LOW FROUDE FLOWS

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INTRODUCTION

Limited water supplies are currently available in most coastal areas to meet municipal and industrial demands. As these areas continue to grow additional water supplies must be developed to meet their needs. Diversion structures and low head dams will be built as part of these expanded water supplies. Typically, these structures are comparatively low and their spillways will operate at low Froude numbers. Palmetto Bend Dam stilling basin (5) is an example of a low Froude number structure modeled recently in the Bureau of Reclamation, E&R Center's Hydraulic Laboratory and the recommended design is quite different from available low Froude number designs (1, 2, 4). As a result, hydraulic model investigations were performed to develop a design that would be suitable for a low Froude number stilling basin. The design developed during these studies will usually be adequate without model tests, unless approach or outlet flow is asymmetrical or unless testing is needed to develop a smaller stilling basin.

Some of the criteria developed from the current model study were location, size and type of baffle piers, chute blocks, end sills, length of the basin, and tailwater depth. The above criteria and guidelines from previous studies were combined to formulate the design guidelines recommended for the low Froude number hydraulic jump stilling basin.

LABORATORY MODEL AND TEST PROCEDURE

The study was conducted in a 30-inch (762-mm) deep, 30-inch (762-mm) wide, and 38-foot (11.58-m) long flume. An overflow crest was placed 13 inches (330 mm) above the floor of the model, followed by a 2:1 inclined chute and a horizontal floor. Both sides of the flume were constructed from clear plastic in the 28-foot (8.53-m) long center section that allowed visual observations from the side.

The water was pumped through the laboratory piping to the model and the discharge was measured with Venturi meters. The discharge was varied for each test to obtain the desired Froude number.

TEST PROCEDURES

After reviewing the available data from references 1 through 5 preliminary tests were run for a natural hydraulic jump stilling basin (Basin I), a Saint Anthony Falls (SAF) stilling basin, and the

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Bureau of Reclamation low Froude number basin (Basin IV) (4). The nomenclature for Basin I, Basin III, and Basin IV is used in (4) to specify a stilling basin design for a certain set of conditions.

The stilling basin designs for Palmetto Bend and the SAF stilling basin recommend that baffle piers and end sills be used. Also, the SAF design further recommends that chute blocks be used. These designs were tabulated and compared to Basin III and Basin IV designs. The Basin III design, for a Froude number of 5, was similar to the SAF design and the Palmetto Bend design. Both of these designs worked well. As a result, a stilling basin was built according to the Basin III criteria for a Froude number of about 6 and when tested, it performed very well. Data extrapolated from the Basin III design was used as the initial design for lower Froude number tests. The size, shape, and location of the chute blocks, baffle piers, and end sills were varied from this extrapolated design to obtain the best configuration for Froude numbers from 2.5 to about 6. The optimum size and placement of the chute blocks were established first and then various sizes and locations for the baffle piers were tested. After the location and size of the baffle piers and chute blocks were determined, different sizes and shapes of end sills were placed near the end of the basin to determine the best end sill and location to minimize surface waves and high velocities along the floor which may increase downstream erosion.

MEASUREMENTS AND CRITERIA FOR EVALUATION

Upstream and downstream depths, discharge, length of the basin, wave heights, and the efficiency of the jump were recorded for each configuration tested. The size and location of the stilling basin appurtenances were recorded. Observations of the velocity patterns, surface flow, eddy size, and location were also noted.

The particular stilling basin that had the shortest length with an even flow distribution, minimum wave heights, maximum energy dissipation, and tailwater at or near D_2 (theoretical conjugate depth) was considered the best stilling basin design.

Both the length and the flow patterns of the basin are subjective observations and will vary from observer to observer. The length of the basin (L) was either the distance from the toe of the chute to the point at which the high velocity jet leaves the floor or the distance from the toe of the chute (section 1) to a point immediately downstream from the surface roller. The above criteria were called length of the jump in both reference (4) and the present study. Section 2 was a point downstream from the jump where the tailwater was measured.

The flow patterns observed during the tests were the surface flow, velocity distribution, and the velocity along the floor downstream from the baffle piers. The best flow pattern was that flow which had a stable jet that hit the baffle piers directly and resulted in the following: (a) lower velocities along the floor; (b) the upstream toe of the jump near section 1; and (c) "smooth" surface immediately downstream from the hydraulic jump.

Initially, wave characteristics were observed visually and comments about wave height, length, and surface roughness were noted. Later a wave probe was used to detect the water surface and to measure the wave characteristics. The analog signal from the probe was recorded on a strip chart recorder.

The specific energy at sections 1 and 2 were computed and were used to evaluate the efficiency of the stilling basin. The efficiency of the stilling basin was defined as the difference of specific energy (E_1) between sections 1 and 2 divided by the specific energy at section 1.

PRELIMINARY TESTS

The initial tests were performed on a natural hydraulic jump stilling basin and on stilling basins designed according to the SAF and Bureau of Reclamation Basin IV criteria before tests were run to develop a low Froude number stilling basin. The eight Basin I tests were for Froude numbers from 2.7 to 6. However, the tests for the SAF and Basin IV designs were for a Froude number of approximately 3.5. These preliminary tests were done to gain experience on the performance of the existing designs and to obtain data to compare with the later tests.

Results of the preliminary tests - The flow downstream from a Basin I design is quite smooth at low Froude numbers and the jump can be maintained in the basin if the tailwater depth is at least equal to D_2, the theoretical conjugate depth. Sweepout (the hydraulic jump begins to move downstream from the toe of the chute) will occur in a natural basin if the tailwater is 3 to 5 percent lower than the conjugate depth.

The SAF stilling basin had rough, turbulent flow on the upstream face of the hydraulic jump. The turbulent flow continued downstream from the end sill and much of the energy dissipation occurred there. Consequently, the potential for scour downstream from the end sill is high for an SAF stilling basin unless riprap or other protection is provided.

The flow in the Basin IV tests without an end sill was quite similar to the Basin I tests. However, rough, turbulent flow developed downstream when an end sill was installed. The end sill recommended for the Basin IV appeared to be too large for the flow. Data from the preliminary tests were combined to form dimensionless ratios and were plotted as functions of the Froude number, figures 1, 2, and 3.

On figure 1 the efficiency is shown as a function of Froude number and the data from the Basin I and Basin IV tests are very close to the theoretical maximum energy loss curve shown as a dashed line. The efficiency of the SAF configuration is about 5 percent more efficient than the other configurations. However, the SAF basin tested had an inadvertently low tailwater which caused the apparent increase in efficiency.

The dimensionless length of the stilling basins are shown on figure 2. The dashed line is the length recommended in (4) for a natural

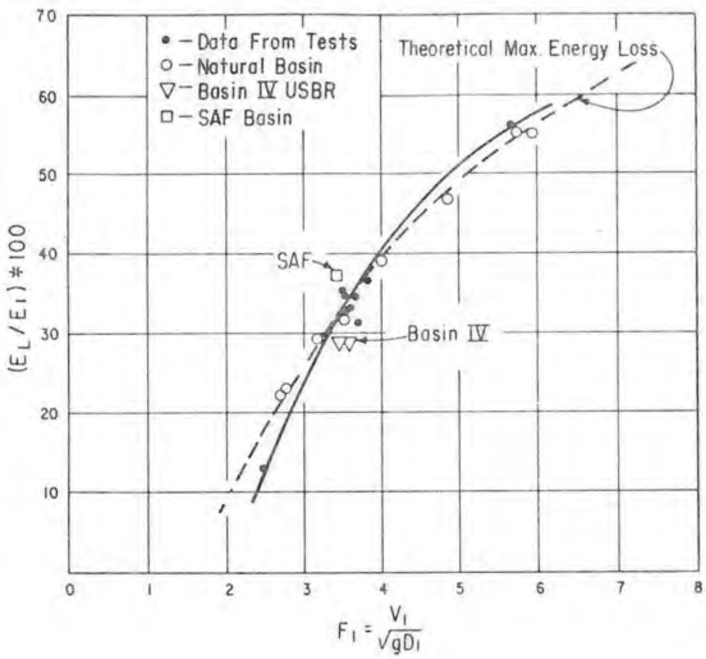

FIGURE 1 - ENERGY LOSS COMPARED TO INCOMING ENERGY

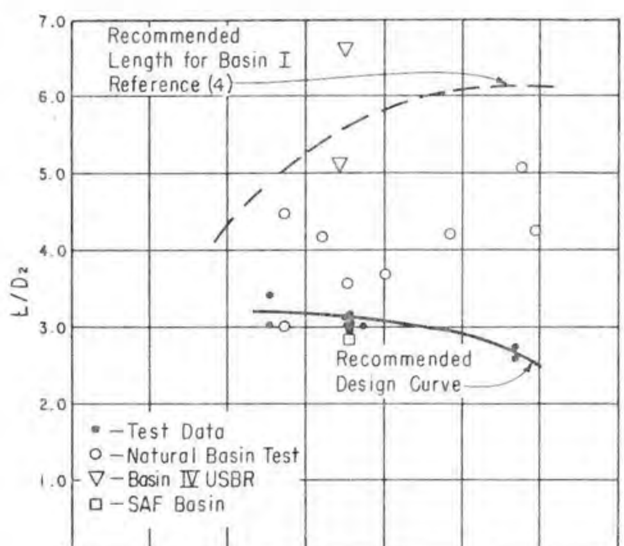

FIGURE 2 - DIMENSIONLESS LENGTH OF STILLING BASIN

hydraulic jump stilling basin, Basin I. The data from the current tests for Basin I are shorter than the length recommended in (4). The difference is probably because the beginning of the jump may have been kept more completely on the sloping chute than the prior test (4) and because differences between observations made by different people. However, each set of data appears to be consistent within itself.

The length of the SAF basin was about 2.8 D_2, considerably shorter than the recommended length, approximately 6 D_2, for Basin I and Basin IV. Two data points are shown as triangles for the Basin IV structure on figure 2. The upper data point is from a test with the end sill and the lower point is without the end sill. The additional length with the end sill was required for the flow to smooth out downstream.

Comparison of the tailwater depth to the theoretical conjugate depth is shown in figure 3. Runs that had tailwater depths higher than those shown in figure 3 had very little energy dissipation even though the flow was very smooth. If the tailwater depth was much below D_2, then a rough wavy surface developed and eventually, as the tailwater was lowered, the hydraulic jump would sweep out of the stilling basin. The best conditions for energy dissipation and flow existed when the tailwater was at or slightly above conjugate depth. Deviations from the theoretical curve are small for both Basin I and Basin IV tests. However, the tailwater of the SAF was slightly low which apparently contributed to the higher efficiency.

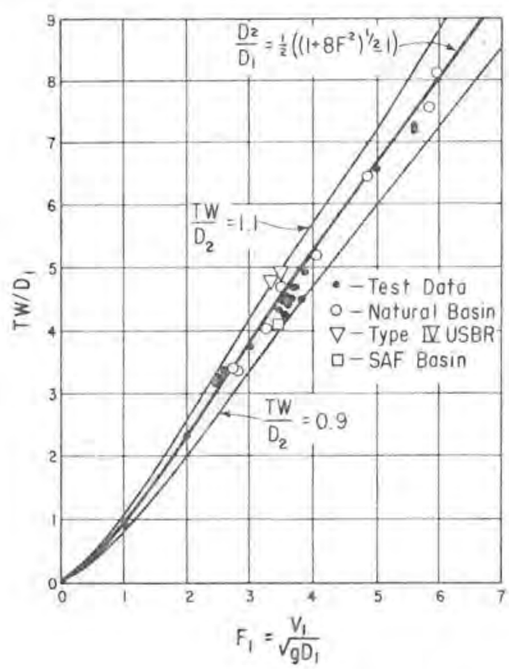

FIGURE 3–RATIO OF TAILWATER TO INFLOW DEPTH

RESULTS OF DEVELOPMENT TESTS

As indicated earlier, the initial design tested was a Basin III stilling basin for a nominal Froude number of about 6. Then, designs for lower Froude numbers were developed from model tests which modified this basic design.

Basin flow patterns - Several different types of flow patterns were characteristic of conditions in the stilling basin during these tests. When chute blocks were placed at the toe of the chute the jet was directed toward the vertical face of the baffle piers and the energy dissipation increased. However, if the baffle piers were too close to the toe of the chute, a rough turbulent flow occurred between the chute blocks and the baffle piers and the jet was deflected upward along the upstream face of the baffle piers. This vertical flow caused a boil above the baffle piers and rough turbulent waves occurred downstream. As the baffle piers were shifted downstream a much smoother flow occurred and the downstream waves diminished.

Baffle piers that were too high caused a secondary jump to occur downstream from them. If the baffle piers were too short, little energy dissipation resulted. Placing the baffle piers downstream from the openings between chute blocks produced a smoother flow than when the baffle piers were not placed between the chute blocks.

Changes in tailwater significantly affected the flow downstream from the baffle piers. If the tailwater depth was much below the conjugate depth, a high velocity jet existed along the floor. These high velocities decreased as the tailwater approached the conjugate depth and most of the kinetic energy in the flow was dissipated by turbulence in the tailwater. However, if the tailwater increased above the conjugate depth the kinetic energy was converted to elevation head and the efficiency of the stilling basin decreased. As a result, a tailwater slightly above the conjugate depth is preferred to a low tailwater condition at the sacrifice of a slight decrease in efficiency.

Rougher flow occurred with a solid end sill than with a dentated end sill of the same height. The dentated end sills tended to enhance the mixing of the higher energy water with the surrounding water and produced a better velocity distribution downstream from the end sill. Also, the tendency for the flow to dive toward the floor was reduced with a dentated end sill. Consequently, a dentated end sill is recommended instead of a solid end sill to minimize the erosion and provide a smoother flow downstream for a wider range of conditions.

RECOMMENDED DESIGN

The design for Froude numbers from 2.5 to 4.5 was developed from the tests of the current study and from design criteria that have been used successfully in previous applications. The recommended design is a rather short stilling basin, L approximately 3 D_2, with chute blocks baffle piers, and dentated end sill.

Chute blocks and baffle piers - The recommended height (H) and width (W) of both the baffle piers and the chute blocks are equal to D_1 and 0.70 D_1, respectively. The recommended spacing (S) between these appurtenances is equal to the width, i.e., $W = S = 0.70\ D_1$. The baffle piers should be placed downstream from the openings between the chute blocks to increase their effectiveness and to decrease the waves. The clear space between the sidewall and the chute blocks should not be less than 0.375 W nor greater than 0.50 W. If the blockage (summation of the widths of baffle piers/width of the channel) is less than 0.40, then partial sections of the baffle piers should be placed along the sidewall to obtain approximately 0.50 blockage. Blockage should be kept between 0.45 to 0.55.

The location of the chute blocks and baffle piers is shown in figure 4. The distance from the chute blocks to the baffle piers (X) varies from 1.4 to about 0.75 times D_2 as the Froude number varies from 2.5 to 5.6, see figure 5.

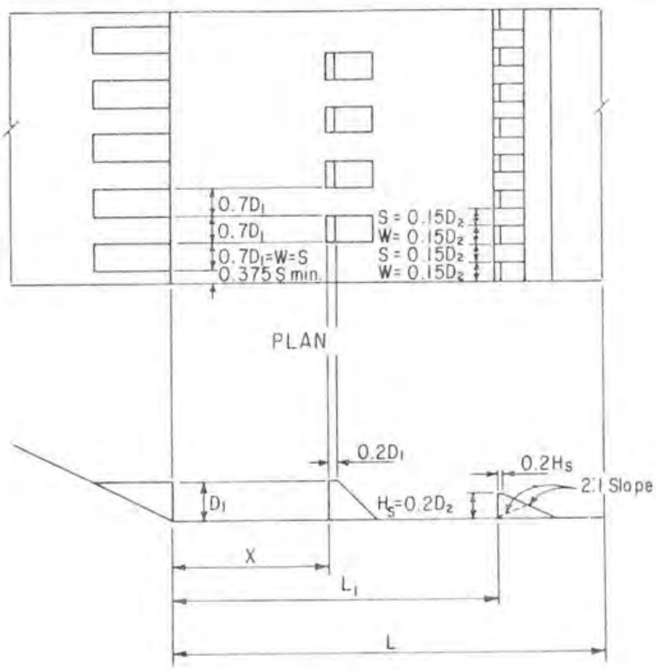

FIGURE 4-RECOMMENDED STILLING BASIN
$(2.5 \leq F \leq 5.0)$

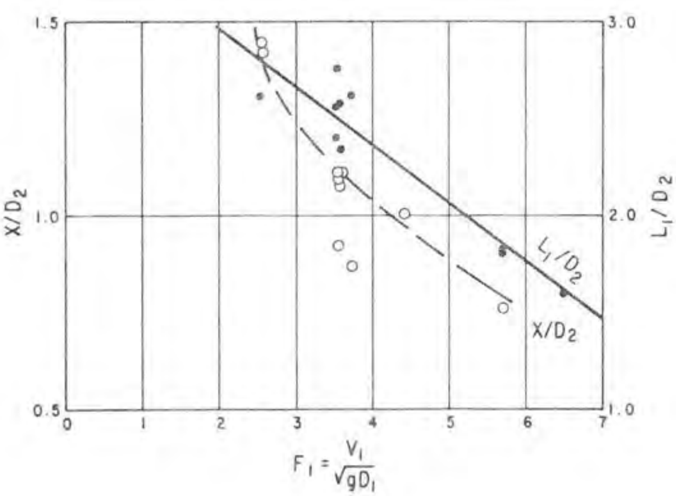

FIGURE 5-DISTANCE TO BAFFLE PIER AND DISTANCE TO END SILL

End sill and basin length - The end sill is placed at the distance L_1 from the chute blocks as shown in figure 4. The height of the end sill is approximately 0.2 D_2 and the slope is shown in figure 4. Width of the dentates and spacing between the end sill dentates are both equal to approximately 0.15 D_2. Generally, blocks should be placed along the sidewalls of the stilling basin.

The recommended length (L) of the basin is shown as the solid line in figure 2. However, the ratio L/D_2 is very close to the value of 3 for all Froude numbers shown and could be used instead of the value obtained from the curves. Suitable scour protection will generally be needed downstream from the end of the stilling basin in highly erodible channels.

Tailwater depth - As indicated on figure 3, the full conjugate depth was required to maintain the jump at the intersection of the horizontal apron and the chute. However, sweepout did not occur for the recommended design when the tailwater was 0.8 times the conjugate depth. It is recommended that the tailwater depth (TW) be maintained at 1.0 to 1.05 times D_2, although the basin will perform well with the tailwater less than D_2.

Energy dissipation - The efficiency data, solid line on figure 1, agree very very well with the theoretical curve for higher Froude numbers and are slightly below this curve at lower Froude numbers. The maximum theoretical energy loss is less than 25 percent for Froude numbers less than 3.0 in a hydraulic jump stilling basin. As a result, the flow downstream still has a considerable amount of energy and it may be better to use an alternate type of energy dissipator such as a baffled apron drop which is a more efficient energy dissipator for Froude numbers lower than 3.0.

DESIGN EXAMPLE

Given: $Q = 250{,}000\ ft^3/s\ (7080\ m^3/s)$ $D_1 = 9.00$ ft (2.743 m)
$b = 370$ ft (112.78 m)

Design of stilling basin $F = \frac{q}{g^{1/2}\ D^{3/2}} = \frac{675.67}{32.2^{1/2}\ 9^{3/2}} = 4.41$

1. $D_2 = \frac{D_1}{2}\left(-1+(8 \times F^2 + 1)^{1/2}\right) = \frac{9}{2} = 51.80$ ft (15.79 m)
2. $TW = 1.05\ D_2 = 54.39$ ft (16.58 m)
3. From figure 2, $L = 3\ D_2 = 155.40$ ft (47.36 m)
4. Chute blocks and baffle piers

   $H = D_1 = 9.0$ ft (2.743 m)
   $W = 0.7D_1 = 6.3$ ft (1.92 m) *6.17 ft (1.880 m)
5. From figure 5, $X = 0.97D_2 = 50.25$ (15.31 m)
6. End sill $H = 0.2\ D_2 = 10.36$ ft (3.16 m)
   $W = 0.15\ D_2 = 7.77$ (2.37) *7.76 ft (2.365 m)

7. From figure 5, $L_1 = 2.24\ D_2 = 116.03$ ft (35.37 m)

*Adjusted values used to obtain an integer number of blocks and spaces.

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