the SAF stilling basin

A STRUCTURE TO DISSIPATE THE DESTRUCTIVE ENERGY IN HIGH-VELOCITY FLOW FROM SPILLWAYS

Agriculture Handbook No. 156

Agricultural Research Service
in Cooperation with the
Minnesota Agricultural Experiment Station
and the Saint Anthony Falls Hydraulic Laboratory

UNITED STATES DEPARTMENT OF AGRICULTURE

PREFACE

This publication is a condensed report of the research that led to the development of the St. Anthony Falls (SAF) stilling basin. It is prepared especially for the use of those who have occasion to design this efficient and economical outlet structure for dissipating the destructive energy in the high-velocity flow at the exit end of chutes, dams, closed conduit spillways, and similar structures.

The experimental work begun in January 1941 was completed in December 1943. The results of the tests were first reported in a processed publication in December 1943 that was revised in May 1949 (SCS–TP–79). A detailed report on the research has been published in the Transactions of the American Society of Civil Engineers, volume 113, 1948, "Development and Hydraulic Design, Saint Anthony Falls Stilling Basin."

This cooperative study in the solution of problems concerning the hydraulics of soil and water conservation structures was made by the staff of the Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, in cooperation with the Saint Anthony Falls Hydraulic Laboratory and the University of Minnesota Agricultural Experiment Station.

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a structure to dissipate the destructive energy in high-velocity flow from spillways

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THE PROBLEM

The research summarized in this publication is a direct result of the need for a stilling basin to dissipate the energy in the high-velocity discharge from culverts, chutes, and other types of spillway.

Engineering literature abounds with descriptions of stilling basins located at dams throughout the world. Each structure, however, had been individually designed for a specific location. Additional studies were required to adapt a design to other locations.

When the SAF stilling basin study was initiated in 1941, at the request of the United States Soil Conservation Service, little had been accomplished toward the development of a universal design. In general, the structures built by the Soil Conservation Service are of such size that few of them can economically justify the individual model studies that proved so profitable in the development of stilling basins for large dams. It was essential, therefore, that an efficient and economical stilling basin be developed and that design rules be formulated so future stilling basins could be designed without recourse to further model studies.

PREVIOUS WORK

A study of the literature on stilling basins carried out in 1941 revealed only two investigations leading to the development of generalized stilling basin designs. To the writer's knowledge, the only additional generalized studies that have been published to July 1958 are those by Bradley and Peterka (*5–11*).[1] In the simple stilling basin studied by Stanley (*18*), the energy in the high-velocity flow is absorbed in a pool formed by a sill or low dam. The Schoklitsch energy dissipator (*17*) is similar to the simple stilling basin in that an end sill is used to form a pool but the jet enters the pool above its bottom. This type is, therefore, somewhat more efficient than the simple stilling basin. Although both the Stanley and the Schoklitsch stilling basins are undoubtedly satisfactory in dissipating energy, a smaller and more economical stilling basin was needed.

THE TEST PROGRAM

Exploratory tests were made on the hydraulic jump, the Schoklitsch, and other published designs of stilling basins. Analytical studies were also made of several other stilling basin designs. As a result of these preliminary studies, some stilling basins were eliminated from further consideration because of their inferior performance in dissipating energy while others were eliminated because their size and cost for equivalent performance were greater than for the more efficient stilling basin.

On the basis of the exploratory tests, the rectangular stilling basin, developed by the United States Bureau of Reclamation and described by Warnock (*19*), was selected for further study. This stilling basin had chute and floor blocks to dissipate the energy and an end sill to deflect the stream away from the bed. The length of the stilling basin was 75 percent and the depth 85 percent of the hydraulic jump length and depth, respectively, but the indications were that the size could be reduced still further. Using this basic form of stilling basin, studies were directed toward determining the minimum dimensions for efficient energy dissipation and the laws governing the design of the various elements making up the basin.

The test program was divided into three parts: (1) The culvert-outlet series in which the basin proportions were determined for a narrow range of the Froude number; (2) the flume-outlet series of check tests, which covered a large range of the Froude number; and (3) the turbine-room series of large-scale check tests. The results of these tests are discussed in this publication.

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[1] Italic numbers in parentheses refer to Literature Cited, p. 14.

LABORATORY FACILITIES AND TEST METHODS

All experiments on the SAF stilling basin were made at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota, Minneapolis. The laboratory is located on Hennepin Island at St. Anthony Falls in the Mississippi River. Up to 300 c. f. s. can be diverted from the river above the falls and returned to the river below the falls after dropping about 50 feet through the laboratory. Water for the various experiments is obtained through pipes connected to a supply canal running the full length of the laboratory.

The culvert and flume series of tests were conducted in a channel 24 inches deep, 18 inches wide, and 8 feet long; the turbine-room series in a channel 6 feet wide and 24 feet long. Since it was impossible to observe from above the operation of the stilling basin under the jet and "white water," all tests were conducted on half-models; that is, the models were split along their centerline and one-half of the model was pressed against a glass plate through which the action of the stilling basin could be observed. Check tests showed that identical results can be obtained from either full or half models. A glass observation panel 8 feet long was located on one side of the 18-inch channel and a panel 2 feet high and 12 feet long on the side of the 6-foot channel; the model centerlines were located along the face of the panels.

Water for the culvert and flume series was obtained through a 4-inch pipe and the discharge controlled by a 3-inch gate valve. The rate of flow was measured by a calibrated 1-foot type HS flume. Water for the turbine-room series was obtained through an 18-inch pipeline that was reduced to 12 inches before reaching the model. The rate of flow was controlled by a 12-inch gate valve and measured by the calibrated pressure difference across the 18-inch by 12-inch reduction, by a calibrated 1.5-foot type H flume, or by a Pitot tube located at the stilling basin entrance.

For the culvert series of tests, the approach to the models was a 3-inch square pipe. The depth of flow at the entrance to the stilling basin was determined by the discharge and the width of the open channel transition used between the pipe and the stilling basin. The depth at the stilling basin entrance for the flume and turbine-room series was set by means of adjustable gates located just upstream from the models. For these series it was possible to regulate both the depth and velocity at the stilling basin entrance. The approach channel width was 3 inches for the flume series and 1 foot for the turbine-room series.

All models were made of wood—waterproof plywood for the smaller models and pine for the larger models.

The tailwater depth was controlled by stop logs located in both channels at the downstream end of the test section. Depths and sand-contour elevations were measured with point gages located on traveling carriages. Centerline profiles of the water surface and eroded sand bed were sketched on data sheets with the aid of a grid of uniformly spaced strings placed against the glass observation panels.

The stream bed downstream from the stilling basin was formed in concrete sand. The effectiveness of each arrangement of stilling basin in removing the destructive energy in the water was measured by the erosion of this sand bed. The loose sand was scoured to its approximate ultimate depth in 30 minutes, and this length of run was used for the culvert and flume series of tests. Two-hour runs were found to be more satisfactory for the large-scale turbine-room series.

Before beginning each experiment, the stream bed was filled in with sand and a small stream of water was used to fill the channel without eroding the stream bed. At the beginning of the run the valve was opened quickly to give the desired discharge and at the end of the run the valve was closed quickly. Data on the discharge, tailwater level, and water-surface profile were obtained during the run. Photographs were made during many runs. After the run the sand bed was drained and the erosion was recorded.

The procedure used in determining the best proportions of the various elements making up the stilling basin was to run a group of tests and make changes on only one element between each test, so that any differences observed in the performance of the stilling basin could be attributed to the change in the pertinent element. This single element was varied in shape, size, or position until the best proportions and location had been ascertained. Other elements were then studied in like manner until the best proportions of all parts of the stilling basin had been tentatively determined. Because of the interdependency of the various elements, it was necessary to repeat certain steps to ascertain the effect of subsequent changes on elements studied previously.

After ascertaining the most satisfactory stilling basin proportions for a single rate of flow, the dimensions were varied for other rates of flow to determine the laws governing the proportions of the stilling basin and its elements. All these tests were part of the culvert-outlet series. Both the flume-outlet and turbine-room series were check tests. The only important revisions in the design resulting from the tests with other rates of flow were in the end sill height and the wingwall shape and position. All changes indicated as a result of the check tests were made and verified.

HYDRAULIC JUMP

All the dimensions of the SAF stilling basin are related, either directly or indirectly, to the hydraulic jump. The theoretical equation for the hydraulic jump is

$$d_2 = -\frac{d_1}{2} + \sqrt{\frac{2V_1^2 d_1}{g} + \frac{d_1^2}{4}}$$

where d_2 is the depth after the jump, d_1 the depth preceding the jump, V_1 the velocity preceding the jump, and g the acceleration due to gravity (32.2 feet per second per second). The derivation of this equation can be found in most books on hydraulics; for example, the "Handbook of Hydraulics" (*15, pp. 8–23 to 28*). Numerous experiments by others have proved the validity of this equation, which can be simplified to

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

where the Froude number $\boldsymbol{F}$ is given by the equation

$$\boldsymbol{F} = \frac{V_1^2}{gd_1} \qquad (1)$$

This dimensionless number ($\boldsymbol{F}$), a constant for similar flow conditions in the model and the prototype, is also used in the determination of the size of the stilling basin.

The length of the hydraulic jump is assumed to be $5d_2$, after Bakhmeteff and Matzke (*1*).[3]

TEST RESULTS

The SAF stilling basin design was developed and verified as a result of 271 tests. The number of tests in each series and the range of the variables are given in table 1, where Q is the discharge, $\boldsymbol{R} = V_1 d_1/\nu$ is the Reynolds number, and ν is the kinematic viscosity. The tests made on each element comprising the SAF stilling basin will be discussed separately.

Length of Basin

The full length of the rectangular stilling basin described by Warnock (*19*) was not utilized in dissipating the energy in the water. (The length of this basin, L_B, was 75 percent of the hydraulic jump length, or, $L_B = 0.75 \times 5d_2 = 3.75d_2$.) The stilling basin was shortened in steps until a minimum length equal to $0.70d_2$ was reached. Surprisingly, the depth of the scour hole was not increased by this shortening until a length of stilling basin less than $1.25d_2$ was tested. The channel erosion was markedly but not dangerously increased when $L_B = 1.00d_2$. When the basin length was $0.70d_2$, the scour at the end of the stilling basin as well as in the downstream channel was considered excessive and the energy dissipation in the stilling basin was poor. A stilling basin length of $1.25d_2$ was used in subsequent tests in which the positions and sizes of the other elements making up the basin were investigated. The Froude number was about 30 for tests up to this point.

Further study of the stilling basin length was initiated after tentatively determining the best sizes and locations of the chute and floor blocks and the end sill. These tests covered a range of the Froude number from 3 to 150 and were part of both the culvert and flume-outlet series. As a result of these tests, it was discovered that the stilling basin was too short for Froude numbers less than 30 and longer than necessary for larger Froude numbers. The stilling basin length, therefore, was varied for each of 12 values of $\boldsymbol{F}$ until the best length was determined. The performance of each length of basin was "rated" and plotted, with L_B/d_2 and $\boldsymbol{F}$ as coordinates, and a curve drawn through the plotted points. Both the experience obtained during the experiments and the plotted data were used in locating this curve. The equation of this curve,

$$\frac{L_B}{d_2} = \frac{4.5}{\boldsymbol{F}^{0.38}} \qquad (4)$$

is suggested as giving a minimum safe length of stilling basin; it is conservative, but not to the point where the material in the outlet is wasted.

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[2] Numbers in parentheses opposite the equations refer to the equations listed on the design chart, pp. 8 and 9.

[3] Bradley and Peterka (*5, 6*) show that the hydraulic jump length varies with the Froude number, reaching a maximum length of about $6.1d_2$. However, this difference in the length has no effect on the SAF stilling basin because the hydraulic jump length does not enter directly into the SAF design, and the tests on the SAF stilling basin covered the practical range of Froude numbers.

TABLE 1.—*Tests of SAF stilling basin and range of test variables*

Series	Tests	Q	V_1	d_1	d_2	$\boldsymbol{F}$	$\boldsymbol{R} \times 10^{-3}$
	Number	*C. f. s.*	*F. p. s.*	*Ft.*	*Ft.*		
Culvert outlet	100	0. 09 to 0. 4	4. 3 to 12	0. 04 to 0. 17	0. 17 to 0. 8	3 to 57	12. 7 to 45
Flume outlet	108	. 04 to . 8	2. 8 to 22	. 05 to . 15	. 13 to 1. 8	5 to 200	14. 2 to 237
Turbine room	66	. 40 to 21.	9. 7 to 44	. 03 to 1. 27	. 49 to 5. 5	7 to 288	40. 6 to 2, 100
Total tests and total range in variables.	274	. 04 to 21.	2. 8 to 44	. 03 to 1. 27	. 13 to 5. 5	3 to 288	12. 7 to 2, 100

Equation 4 was developed for a range of the Froude number from 3 to 150, but it was later used to design experimental stilling basins having values of $\boldsymbol{F}$ as high as 300. The results of all subsequent tests show that stilling basin lengths determined from equation 4 are satisfactory.

Chute Blocks

The chute blocks, located at the entrance to the stilling basin, serve to increase the effective depth of the entering stream, break the stream up into a number of small jets, and help create the turbulence required for effective energy dissipation.

The original height of the chute blocks was d_1, and the width and spacing, $0.75d_1$. A test on a solid chute block, such as is used in the Schoklitsch energy dissipator, showed that less energy was dissipated in the stilling basin and that flow conditions in the channel downstream from the stilling basin were not so good. A second test was made in which the tops of the chute blocks were sloped to direct the jets at the floor blocks. The result of this change was to increase the depth of erosion near the end of the stilling basin.

The chute blocks used for all subsequent tests had a height of d_1 and a width and spacing of $0.75d_1$. These proportions proved to be entirely satisfactory. It makes no difference in the performance of the stilling basin whether a chute block or a space is next to the sidewall as long as the blocks are symmetrical about the centerline of the outlet.

Floor Blocks

Energy is removed from the water by impact against the floor blocks and considerable turbulence is created by them.

The first tests on the floor blocks were made to determine their best longitudinal position. These tests show that it is equally as bad to have the distance between the chute and floor blocks too short as it is to have the distance between the floor blocks and end sill too short. If the distance between the chute and floor blocks is too short, the blocks act like a solid chute block. If the distance between the floor blocks and end sill is too short, the blocks and sill act as a unit in deflecting the jet upward.

Nearly identical results were obtained when the floor blocks were located $L_B/3$ and $L_B/2$ from the upstream end of the stilling basin. The results for the $L_B/3$ spacing were slightly better, but the difference probably is insignificant. The floor blocks were located $L_B/3$ from the upstream end of the basin for all subsequent tests. No reason was discovered for changing their longitudinal location as a result of these tests.

Floor blocks were tried with heights both greater and less than d_1. This height of floor block was either as good as or better than greater and lesser heights. Accordingly, a floor block height equal to d_1 was used for subsequent tests.

The width and spacing of the floor blocks should be the same as for the chute blocks. However, for those stilling basins in which the sidewalls diverge in plan, the width and spacing of the floor blocks should be increased over the chute block width and spacing to compensate for the greater stilling basin width at the floor block location.

No floor block should be located closer to the stilling basin sidewall than $3d_1/8$. Floor blocks located closer cause a high boil that might overtop the sidewall.

Insufficient water can pass between the floor blocks if they occupy too much of the stilling basin width; they then act more like a sill than like individual blocks. The test results show that satisfactory conditions exist when the floor blocks occupy between 40 and 55 percent of the stilling basin width. The aggregate width of all floor blocks, therefore, should be held within these limits, even if it is necessary to reduce the width of the floor blocks to do so.

The floor blocks always should be placed downstream from the openings in the chute blocks to break up the jets issuing from between the chute blocks and passing along the stilling basin floor. A single test made with the floor blocks in line with the chute blocks was sufficient to show the inferiority of this arrangement.

The floor blocks may be piers square in plan with vertical faces, or their downstream faces may slope as shown on the design chart.

Force on Floor Blocks

A knowledge of the forces exerted on the floor blocks is necessary for their structural design. No tests were made to determine these forces. It is possible, however, to compute the maximum probable forces, and the results of experiments by others are available to modify these computed values.

The impact force on the floor blocks required to turn the flow 90° is given by the equation $F=AV_1^2w/g$, where F is the total force, A is the area of the face of the blocks, and w is the unit weight of water (62.5 pounds per cubic foot). It is convenient to write the impact force in terms of d_1 and $\boldsymbol{F}$, since both of these values are required in the design of the stilling basin. The force per unit width of the floor block, f, is

$$f=wd_1^2\boldsymbol{F}$$

This equation gives the maximum impact force on the floor blocks per unit width of block. The equation assumes that all the water approaching the block is turned at right angles to its original direction. Much of the water changes direction only slightly, so the actual force must be considerably less than the computed maximum. Other factors that influence the force on the floor blocks are the shape, width, and spacing of the blocks, the effect of the chute blocks, and the fact that the mean velocity at the floor blocks is reduced by the chute blocks and the roller. Such information as is available regarding the effect of these factors will be presented.

The forces on stepped blocks and streamlined blocks measured experimentally at the Massachusetts Institute of Technology have been reported by Harleman (*14*). The stepped blocks approximate the shape of the vertical-faced blocks used in the SAF stilling basin. Harleman states: "The maximum force exerted by the baffle piers is of the order of 20 percent of the pressure force due to the downstream depth." Since the downstream force is applied across the full width of the stilling basin and the stepped blocks occupied 50 percent of the basin width, the maximum measured force per unit width of blocks is 40 percent of the pressure force per unit width due to the downstream depth. Using this latter figure, it is found that the maximum force per unit width of block varies from 27 percent of the theoretical value for $\boldsymbol{F}=3$ to 38 percent of the theoretical force for $\boldsymbol{F}=300$.

Unpublished results of tests made at the St. Anthony Falls Hydraulic Laboratory in connection with a model study of the Chippewa River Reservoir Dam of the Northern States Power Co. substantiate the MIT values. Piezometric pressures were measured on the face of a baffle pier located below a Tainter gate, and the pressures were integrated to determine the total force on the baffle. Forces determined for three different rates of flow amounted to 43 percent, 24 percent, and 27 percent of the impact forces computed as outlined above.

In view of these data and until better information is available, it is suggested that the force on the floor blocks exerted by the approaching stream be taken as 40 percent of the computed impact force, or

$$f=0.4\ wd_1^2\boldsymbol{F}=25\ d_1^2\boldsymbol{F}$$

End Sill

The end sill, located at the downstream end of the stilling basin, deflects the bottom currents upward and away from the stream bed. In addition, a ground roller is created under the deflected stream, which brings bed material from downstream and deposits it at the end of the stilling basin.

The height of the end sill, c, for the culvert-outlet series was made $d_2/7$. This end-sill height proved to be satisfactory for the narrow range of the Froude number for which it was derived, but the equation was inadequate for a larger range of the Froude number.

A thorough study of the end-sill height for values of $\boldsymbol{F}$ from 5 to 200 was made as part of the flume-outlet series of tests. The best height of end sill for each set of otherwise constant conditions was selected, and the selected values were found to be independent of the Froude number. However, when c/d_2 was plotted against the Reynolds number $\boldsymbol{R}$, a well-defined curve was obtained, although there is no reason to believe that such a relationship should exist. A study of the equation for this curve showed that the height of the end sill was unbelievably low for values of $\boldsymbol{R}$ within the practical range. This naturally cast suspicion on the form of the end-sill height equation and led to the turbine-room tests, which were made at higher Reynolds numbers.

The turbine-room tests confirmed the opinion that the end-sill height was too low for the higher values of $\boldsymbol{R}$ and indicated that c/d_2 was independent of both $\boldsymbol{F}$ and $\boldsymbol{R}$. A tentative equation ($c=0.07d_2$) was derived early in the test program. This equation was checked by other tests until it became apparent that this end-sill height would be satisfactory. Subsequent tests were made to verify this equation.

A review of the data obtained during the flume-outlet series of tests shows that satisfactory erosion conditions were obtained when $c=0.07d_2$. The higher end sills given by the equation containing $\boldsymbol{R}$ produced slightly better erosion patterns for the lower values of $\boldsymbol{R}$, but the difference is so small as not to warrant the use of separate equations. The recommended equation for the height of the end sill is

$$c=0.07d_2 \tag{6}$$

Tailwater Depth

Use of the blocks and end sill in the stilling basin permits the depth of the tailwater above the stilling basin floor level to be decreased over that for the theoretical tailwater depth of the hydraulic jump. Warnock (*19*) recommended a 15-percent reduction, so that the actual tailwater depth, d'_2, would be $0.85d_2$. Tests were made to check this figure.

If the tailwater depth is too low, the roller on the hydraulic jump will be washed out of the stilling basin and the floor blocks and end sill will simply deflect the stream and break it up. The broken-up stream will land on the water surface some distance downstream from the outlet and erode the bed only slightly, with the depth of the scour hole near the end of the stilling basin remaining unchanged. The structure will not be endangered thereby, but the energy dissipation in the stilling basin is poor and the spray may prove objectionable.

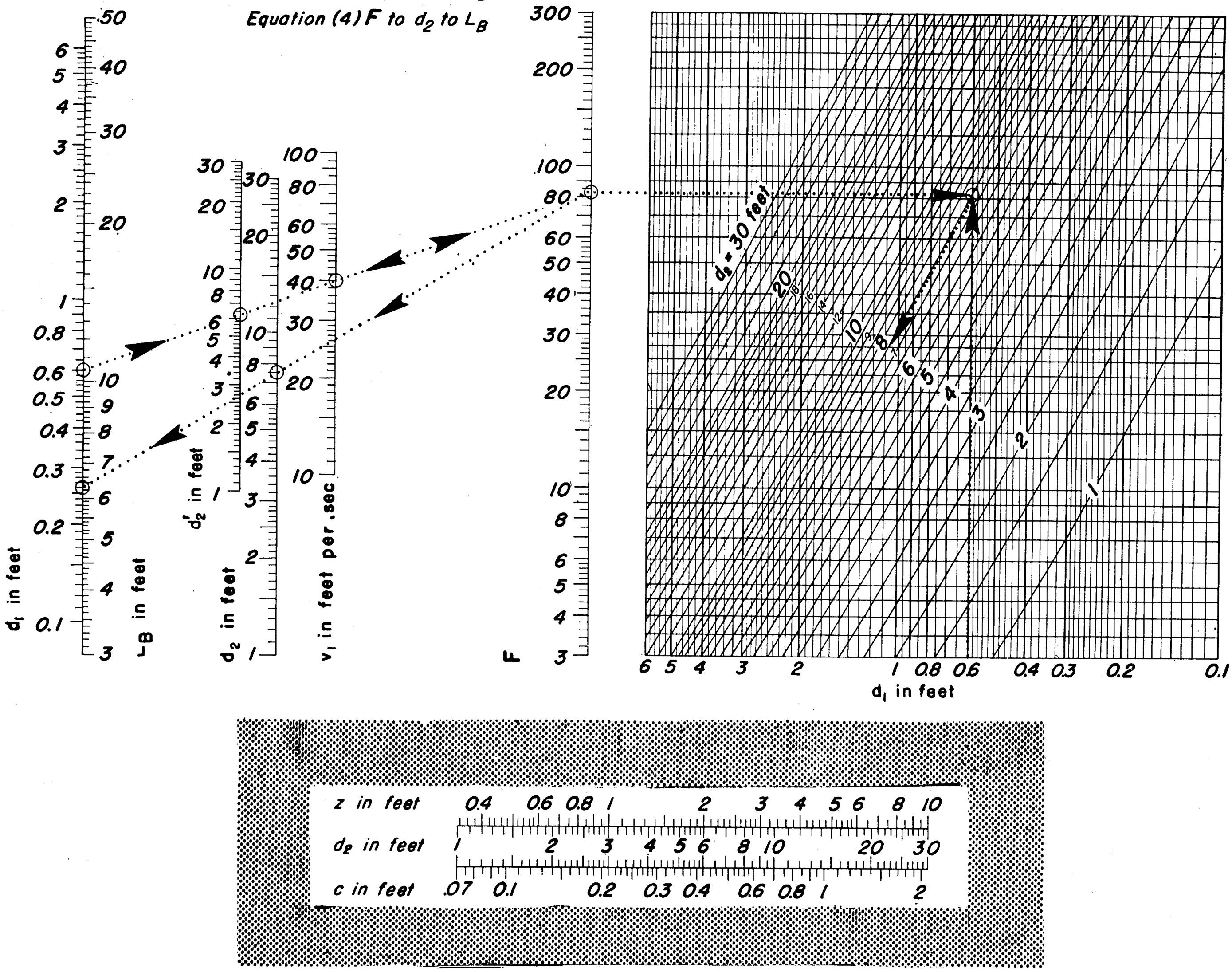
In determining the minimum permissible value of d'_2, the tailwater depth was decreased until the roller was washed out of the stilling basin. The relative tailwater depth at which this occurred was plotted against $\boldsymbol{F}$. Originally the relative tailwater depth was assumed to be d'_2/d_2. When a paper (*2*) describing development and hydraulic design of the SAF stilling basin was published, however, one of the discussers showed that plotting the ratio d'_2/d_1 permitted the derivation of a relationship that is continuous over the range of Froude numbers covered by the tests. As a result of this discovery, d'_2/d_1 was plotted against

A. SOLUTION OF EQUATIONS (1), (3) AND (4)

Procedure. Equation (1) d_1 to v_1 to F
Equation (3) d_1 to F to d_2'
Equation (4) F to d_2 to L_B

B. SOLUTION OF EQUATION (2)

Procedure: F to d_1 to d_2



C. SOLUTION OF EQUATIONS (5) AND (6)

Procedure: Equation (5) d_2 to z
Equation (6) d_2 to c

D. EXAMPLE

GIVEN: $d_1 = 0.6$ ft. and $v_1 = 40$ ft. per sec.

SOLUTIONS OF EQUATIONS (using curves and nomographs)

(1) $F = 83$ (2) $d_2 = 7.4$ ft. (3) $d_2' = 6.1$ ft.

(4) $L_B = 6.3$ ft. (5) $z = 2.48$ ft. (6) 0.52 ft.

E. DESIGN EQUATIONS

(1) $F = \frac{v_1^2}{g d_1}$

(2) $d_2 = \frac{d_1}{2}\left(-1 + \sqrt{8F + 1}\right)$

(3) $d_2' = 1.4 d_1 F^{0.45}$

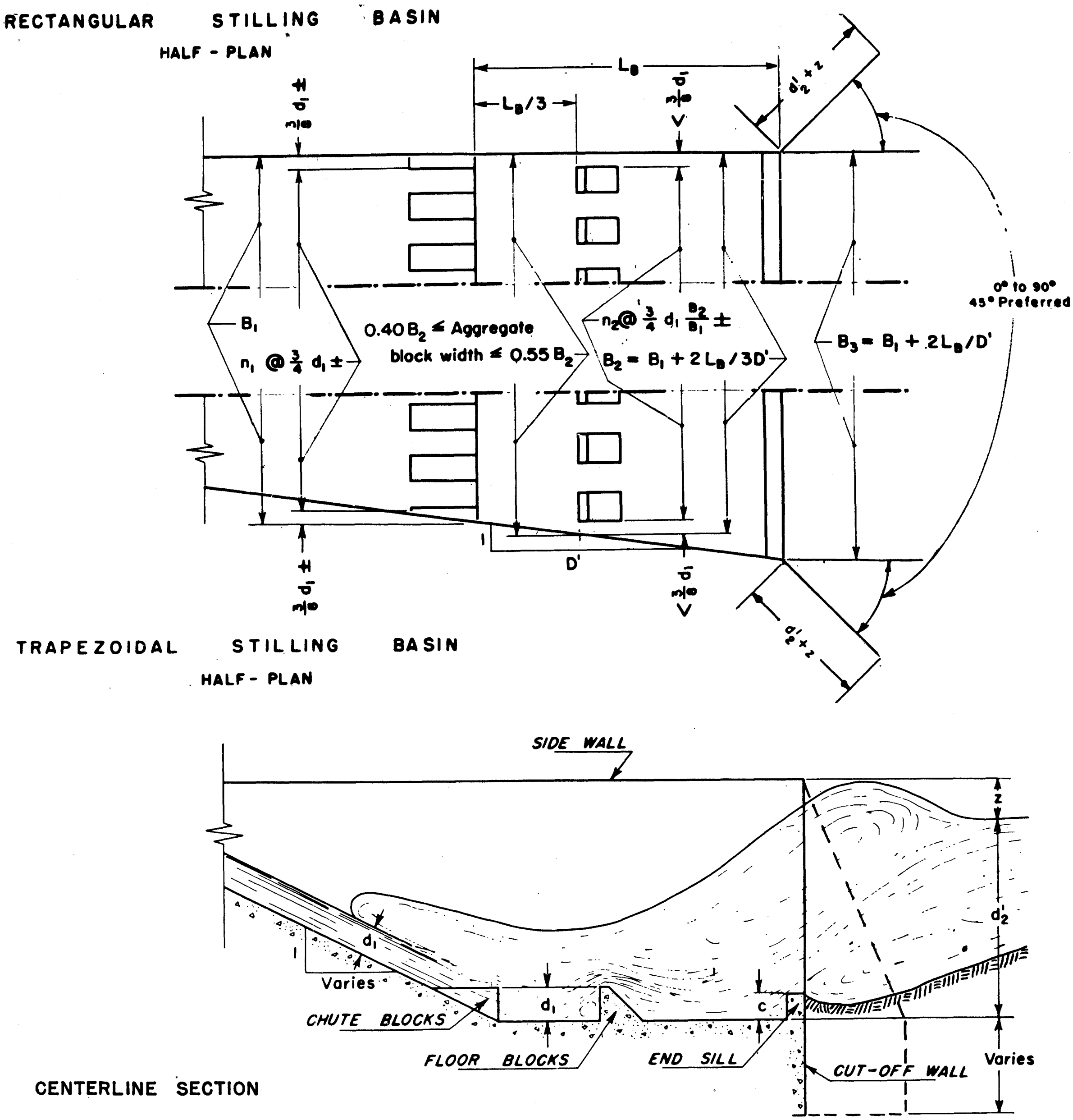
(4) $L_B = \frac{4.5 d_2}{F^{0.38}}$

(5) $z = d_2/3$

(6) $c = 0.07\, d_2$

FIGURE 1 - DESIGN CHART for SAF STILLING BASIN

Agricultural Research Service, U. S. Department of Agriculture, in cooperation with the Minnesota Agricultural Experiment Station and the St. Anthony Falls Hydraulic Laboratory, University of Minnesota.



F. PROPORTIONS OF THE SAF STILLING BASIN

G. DEFINITIONS OF SYMBOLS

B_1 - width of stilling basin at upstream end, in feet

B_2 - width of stilling basin at floor blocks, in feet

B_3 - width of stilling basin at downstream end, in feet

c - height of end sill, in feet

d_1 - depth of flow at entrance to stilling basin, in feet

d_2 - downstream depth computed by momentum equation for the hydraulic jump, in feet

d_2' - water surface elevation in downstream channel above stilling basin floor, in feet

D' - side wall divergence, D' longitudinal to 1 transverse

F - the Froude number

g - acceleration due to gravity, in feet per second per second

L_B - length of stilling basin, in feet

V_1 - velocity at entrance to stilling basin, in feet per second

z - height of stilling basin side walls above maximum tailwater level, in feet

$\boldsymbol{F}$ and an enveloping curve drawn above the relative depths at which the roller is washed out of the stilling basin. The equation of this curve is

$$\frac{d'_2}{d_1}=1.4\boldsymbol{F}^{0.45} \qquad (3)$$

Sidewall Height

The flow in the stilling basin is very turbulent, and, as a result, the water surface is so rough that some freeboard above tailwater level is necessary if overtopping of the sidewalls is to be prevented. In addition to the surface roughness, a standing wave, or boil, is caused by the floor blocks and end sill, which in itself requires freeboard above the tailwater level. For Froude numbers less than about 20, the crest of the boil is in the stilling basin, whereas, for higher Froude numbers, the boil crest occurs downstream from the end of the basin and its full height need not be considered in designing the sidewall height.

Average profiles of the water surface in the stilling basin were obtained for all series, but the maximum height of splash was obtained for only the turbine-room series. It is from these latter tests that the height of the sidewall is determined.

The maximum height of the splash z_{max} in the stilling basin was divided by d_2. There is considerable scatter to the data, but z_{max}/d_2 is apparently independent of $\boldsymbol{F}$. The range of z_{max}/d_2 is from -0.02 to 0.31. A study of the data shows that if the height of the stilling basin sidewall, z, above the maximum tailwater level is given by the equation

$$z=d_2/3, \qquad (5)$$

the freeboard will be sufficient to keep the splash in the stilling basin. Because of the scatter in the data, the freeboard provided by this equation will, in some cases, be greater than is necessary to protect fully the structure, but the safety factor is not excessive for the average case.

Wingwalls

Wingwalls at the end of the stilling basin are used as retaining walls to hold back the earth fill. The ordinarily used wingwall is rectangular in downstream elevation. Since the scour around the end of this wall is severe, other wingwall shapes were investigated.

The principal cause of the scour around the end of the wingwall is an eddy along each side of the downstream channel that is driven by the stream leaving the stilling basin. It is imperative that the concentration of the flow from this eddy be kept off the stream bed. Two methods can be used to prevent the eddy from attacking the stream bed: (1) A submerged extension of the wingwall, having a height equal to half the tailwater depth and a length equal to 0.6 of the sidewall height (the minimum length of rectangular wingwall used in the experiments was 0.4 of the sidewall height); or (2) a wingwall of triangular shape in downstream elevation, the top having a slope of 1:1. The triangular shape of wall is recommended, because it is equally as satisfactory in preventing scour as is the extended wingwall and, in addition, requires less material.

Wingwalls have been customarily located perpendicular to the centerline of the outlet structure. Tests have shown, however, that the wingwalls may be extended parallel to the basin centerline if field conditions make it necessary to do so, although the boil height is considerably higher. Nevertheless, the best overall conditions are obtained if the triangular wingwalls are located at an angle of about 45° to the outlet centerline.

Subsequent tests of other types of stilling basins have confirmed the superior performance of the wingwall having a 1:1 top slope located at an angle of 45° to the outlet centerline (*4*, *12*, *13*).

Shape of Basin

The size of the stilling basin varies with the initial flow depth if V_1 does not change; any reduction in d_1 will reduce d_2, the length of the basin, the height of the sidewalls, and the depth of excavation. In addition, a larger percentage of the energy in the water entering the stilling basin will be dissipated. A saving in overall cost of the outlet will ordinarily be possible if a flaring-sidewall transition is placed between the culvert or chute and the stilling basin to accomplish this reduction in d_1 (*3*). In those cases where a transition is used, the diverging transition sidewalls should be extended to form the stilling basin walls. The resulting stilling basin is trapezoidal in plan, as is shown on the design chart, page 8.

A few tests were made on a trapezoidal-shaped stilling basin in the culvert-outlet series. The stilling basin was designed for flow conditions at its entrance. The width and spacing of the floor blocks were multiplied by the ratio B_2/B_1 to compensate for the increase in the width of the stilling basin at their location. All blocks had their axes parallel to the centerline of the basin. Flow conditions in the downstream channel were somewhat improved through the use of the trapezoidal stilling basin. This is because the velocity of the flow was lower at the exit from the basin, and the widening of the stream to fill the downstream channel reduced the size of the eddies along the channel sides near the stilling basin.

Cutoff Wall

A cutoff wall is used at the end of the stilling basin to prevent scour from undermining the basin. Obviously, the depth of the cutoff wall must be greater than the maximum depth of erosion at the end of the stilling basin.

Serious erosion near the end of the stilling basin is prevented by the end sill, which deflects upward the stream leaving the basin. A ground roller under the deflected stream brings material upstream and further aids in preventing erosion.

In the laboratory, the scour sometimes reached an elevation slightly below the floor of the stilling basin, but the scour never reached a depth at the end of the basin greater than the thickness of a floor slab that might be used. Therefore, a cutoff wall of only nominal depth need be used at the end of the stilling basin.

Effect of Entrained Air

Air is ordinarily entrained by the water flowing in chutes laid on a steep slope. This results in a greatly increased depth of flow of the mixture. However, no air was naturally entrained by the water during the model tests because of the low velocities or the short length of channel. Because entrained air may affect the performance of the stilling basin, a few tests were made in which from 10 to 117 percent of air was mixed with the water. The stilling basins were designed as if the water were free of air, and duplicate tests were run both with and without air entrainment. Identical results, within the limits of experimental precision, were obtained from the duplicate tests. Although d_1 is greater when air entrainment occurs, d_2 remains unchanged, since the air separates from the water, owing to the lower velocities in the downstream channel. No increase in sidewall height is required as a result of air entrainment.

The results of these tests show that the effect of air entrainment can be neglected in the design of the SAF stilling basin. The resulting structure will safely handle any flows in which air is entrained.

CONCLUSIONS

The following conclusions are reached as a result of the tests made to develop and verify the SAF stilling basin design:

1. The length of the stilling basin for Froude numbers between 3 and 300 is

$$L_B=4.5d_2/\boldsymbol{F}^{0.38} \tag{4}$$

2. The height of the chute blocks and the floor blocks is d_1; their width and spacing are approximately $3d_1/4$; either a chute block or a space may be located next to the sidewall if the blocks and spaces are symmetrical about the outlet centerline.
3. The floor block criteria are as follows:
   a. The distance from the upstream end of the stilling basin to the floor blocks is $L_B/3$.
   b. No floor block should be placed closer to the sidewall than $3d_1/8$.
   c. The floor blocks should be placed downstream from the openings between the chute blocks.
   d. The floor blocks should occupy between 40 percent and 55 percent of the stilling basin width.
   e. The widths and spacings of the floor blocks for diverging stilling basins should be increased in proportion to the increase in stilling basin width at the floor block location.
   f. The floor blocks may be piers square in plan with vertical faces, or their downstream faces may slope as shown on the design chart.
   g. The force per foot width exerted on the floor blocks by the approaching stream may be taken as

$$f=25d_1^2\boldsymbol{F}$$

4. The height of end sill is

$$c=0.07d_2 \tag{6}$$

5. The depth of the tailwater above the stilling basin floor is

$$d'_2=1.4\boldsymbol{F}^{0.45}d_1 \tag{3}$$

6. The height of the sidewall above the maximum tailwater depth to be expected during the life of the structure is

$$z=d_2/3 \tag{5}$$

7. Wingwalls should be equal in height and length to the stilling basin sidewalls. The top of the wingwall should have a 1:1 slope. Wingwalls flaring at 45° with the outlet centerline are preferred to wingwalls that are perpendicular or parallel to the centerline.
8. The stilling basin sidewalls may be parallel (rectangular stilling basin) or diverge as an extension of the transition sidewalls (trapezoidal stilling basin).
9. A cutoff wall of nominal depth should be used at the end of the stilling basin.
10. The effect of entrained air should be neglected in the design of the stilling basin.

During the tests it was noticed that the performance of the SAF stilling basin was excellent at discharges less than the design discharge. At the design flow the SAF stilling basin provides an economical method of dissipating energy and preventing dangerous stream bed erosion.

APPLICATION OF RESULTS

Design Chart

The results of all the tests on the SAF stilling basin are summarized on the design chart for the SAF stilling basin (fig. 1).

The proportions of a SAF stilling basin can be determined from the chart without the aid of any instrument or any other design chart or table. The use of the design charts is explained thereon, a typical problem is solved, and the principal dimensions determined.

The stilling basin dimensions obtained from the design charts will result in a good design. Slight variations in the dimensions, however, will have little or no effect on the performance of the basin. To simplify the construction, all odd dimensions should be changed to even dimensions.

Solution of a Typical Problem

A rectangular SAF stilling basin is to be constructed at the end of a 3-foot wide chute. The depth and velocity at the end of the chute are 0.6 foot and 40 f. p. s., respectively, the design tailwater elevation is 377.0, and the maximum tailwater elevation in the downstream channel anticipated during the life of the structure is 378.5 for the design discharge of 72 c. f. s.

Reading the principal dimensions from the design charts it is found that: $\boldsymbol{F}=82.8$, $d_2=7.43$ feet, $d'_2=6.13$ feet, $L_B=6.28$ feet, $z=2.48$ feet, and $c=0.520$ foot. In order to simplify the construction, $L_B=6$ feet 3 inches, and $c=6$ or 7 inches can be used without affecting the operation of the structure. The elevation of the top of the sidewalls, which is determined from the maximum tailwater elevation, is $378.5+2.48=380.98$; use 381.00. The force on the floor blocks is $25 \times 0.6^2 \times 82.8=745$ pounds per foot of width.

The elevation of the basin floor is $377.0-6.13=370.87$. The tailwater level and required tailwater depth also should be checked at discharges less than the design value to insure proper stilling action at all flows. Finally, consideration of the possibility that the channel bed elevation—and, as a result, the tailwater level—may become lower in time, suggests that the stilling basin floor be set below the calculated elevation. The amount will depend upon local conditions and the judgment of the designer. The wingwall will have a length of about 9 feet, depending on the sidewall height, and its top a slope of 1 : 1. A cutoff wall under the stilling basin having a depth of 2 feet or more should be used.

Several arrangements of the 6- or 7-inch high chute and floor blocks are possible, the floor blocks being placed $\frac{6 \text{ feet } 3 \text{ inches}}{3}=2$ feet 1 inch, say 2 feet, downstream from the upper end of the basin.

The chute and floor blocks and the spaces between them can be made $0.6 \times \frac{3}{4}=0.45$ foot$=5\frac{1}{2}$ inches, say 6 inches. This gives $36/6=6$ spaces across the stilling basin. Now, locate chute blocks 3 inches from either side of the chute and one straddling the centerline. Two floor blocks can now be located in the basin downstream from spaces between the chute blocks. No floor blocks should be located next to the basin walls. The proportion of the basin width occupied by the floor blocks is $2 \times 6/36=0.33$. This proportion for floor blocks is lower than is recommended. This difficulty can be overcome by making the block width and spacing 8 inches. The proportion then becomes $2 \times 8/36=0.44$. The total force on each block is $745 \times 8/12=500$ pounds.

Another arrangement of the blocks is to make them 6 inches wide as before, but to place half a chute block at each side of the chute and the two other equally spaced blocks between them. Three equally spaced floor blocks can then be used in the basin, one straddling the centerline and the others placed 6 inches on either side of the center block. The block nearest to the sidewall is therefore 3 inches from the sidewall. This is greater than the allowable minimum of $0.6 \times \frac{3}{8}=0.225$ foot$=2\frac{3}{4}$ inches. The proportion of the basin width occupied by the floor blocks is $3 \times \frac{6}{36}=0.50$, a satisfactory figure. The total force on each floor block is $745 \times \frac{6}{12}=372$ pounds.

Arrangement of the blocks is up to the designer. Either arrangement given above would be satisfactory.

Field Experience

The first SAF stilling basin was built in western Iowa in 1944. Since that time a considerable number of SAF stilling basins have been built. The exact number is unknown to the writer; publications describing the design of the SAF stilling basin are readily available for use by anyone without restriction, and there is no way to determine how many stilling basins have been built according to the SAF design.

The writer has seen a number of SAF stilling basins and has had reports on the performance of other stilling basins. All reports received by the writer and all SAF stilling basins observed by him have shown satisfactory performance. The following field structures are known to have handled flows that approach the capacity for which they were designed, so their performance will be described.

The most thorough and complete test of the SAF stilling basin was that performed by William O. Ree (*16*) at the Stillwater (Okla.) Outdoor Hydraulic Laboratory of the Agricultural Research Service. Mr. Ree concluded (*p. 13*):

> Tests of the St. Anthony Falls Stilling Basin during a 2-year period at the Stillwater Outdoor Hydraulic Laboratory showed that the stilling basin was very effective and completely satisfactory. Very little scour of the channel bed occurred. It should be noted, however, that the bed material at the point of discharge was a rather firm clay. A sandy material might have shown a little different result.
>
> . . .
>
> Splash was not an important problem.

Figure 2 shows this stilling basin.

If someone is unduly concerned regarding erosion in sandy material, figure 3 shows a SAF stilling basin at the exit of a 48-inch diameter closed conduit spillway located at an airfield in northwestern Florida. The soil at the site of this structure is a clayey sand. No scour of this readily erodible bed material is evident.

In a monthly report, Glenn H. Baker, Soil Conservation Service engineering specialist, commented on a visit to Spruce Knob Lake, in W. Va., made in 1953, as follows:

> At this visit I had an opportunity to observe the performance of the SAF type stilling basin in operation. During the inspection the gate was completely removed from the opening to the 26-inch diameter drain which caused the maximum planned discharge. The basin performed according to expectations almost exactly as indicated by the model test shown in Ohio. There was a minimum of erosion in the channel below the dam, and the other engineers were impressed with the operation of this type of structure.

The model referred to was one developed for demonstration purposes in which the pipe had a diameter of 1½ inches—one-seventeenth the size of the Spruce Knob Lake pipe.

The third structure that will be mentioned is a SAF stilling basin at the end of a chute. This spillway is located in Crawford County, Iowa. On June 22, 1947, the storm runoff rate exceeded the design capacity of the spillway by 50 percent, this figure being based on information made available to the writer by Floyd Nimmo, construction engineer, through M. M. Culp, Chief, Design and Construction Branch, Engineering Division, U. S. Soil Conservation Service. Figure 4 shows views of this structure taken before and after the excessive storm of June 22, 1947. It is readily apparent from these photographs that the SAF stilling basin gave excellent protection to the downstream channel despite the excessive flow that passed through it.

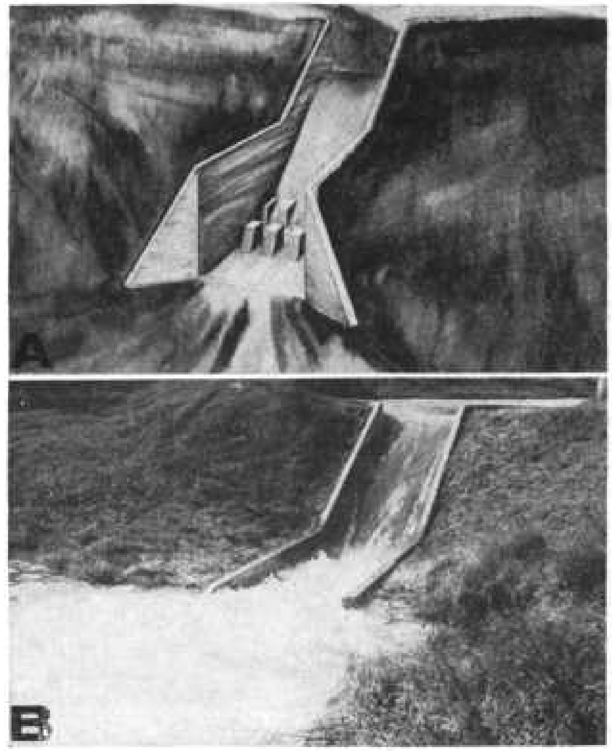


FIGURE 2.—SAF stilling basin at Stillwater (Okla.) Outdoor Hydraulic Laboratory: *A*, Drawing of basin; *B*, with full-capacity flow.

FIGURE 3.—SAF stilling basin at exit of 48-inch closed conduit spillway in northwestern Florida.

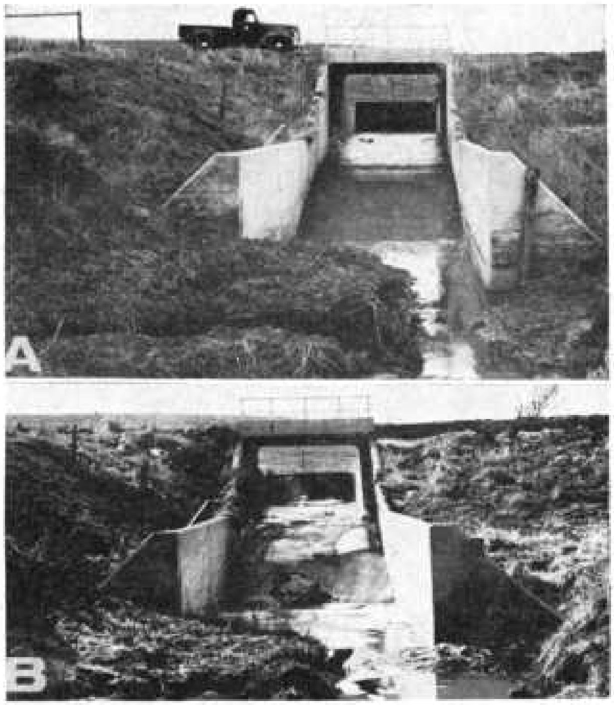


FIGURE 4.—Box inlet chute spillway and SAF stilling basin in Crawford County, Iowa: *A*, Before storm of June 22, 1947; *B*, after storm of June 22, when storm runoff rate exceeded design capacity by 50 percent.

E. I. Rowland, Arizona State Supervisor for the Bureau of Land Management, U. S. Department of the Interior, has furnished a number of interesting photographs of a SAF stilling basin (figs. 5 and 6). In a letter to the writer, dated October 31, 1955, Mr. Rowland writes:

> Enclosed are a few photographs of a drop structure placed across the San Simon Wash in southeastern Arizona. This is a replacement for an earlier design structure which was not adequate and washed out in 1954. This structure, known as the San Simon drop structure, has worked very successfully this year. The peak flow water stood at 6½′ depth in the impounded area above the drop structure. The spillway lip is at elevation 88 feet (assumed) and the peak water within the reservoir was at 94½ foot stage. It was calculated that the maximum flow through the structure at this elevation was approximately 2,200 cfs.
>
> At this peak flow, the hydraulic jump in the box outlet, as indicated by the flow line of water through the lower structure was 13 feet above the floor of the structure at this point. The heavy splash line as indicated by the mud deposits on the side walls [fig. 6] reached 16 feet in height above the floor. The walls are 18 feet high at this point.
>
> It is extremely gratifying to note that the drop structure operated very effectively for volume flow reduction and reduced channel cutting. You will note in the picture [fig. 5,*B*], taken after all flow through the spillway had stopped on September 26, that there was no channel cutting, and practically no cutting around the lower wing walls except that which was caused by foreign drainage on the east wing, which will be corrected.
>
> Of most interest to us was the small sand fan which developed immediately below the lip of the structure and can be noted in the picture taken September 26 [fig. 5,*B*].

SUMMARY

The stilling basin developed as a result of the model studies at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota has become known as the "SAF stilling basin." It has five distinct advantages:

1. The characteristics and proportions of the stilling basin have been determined over a wide range of conditions to be expected in the field; the performance can be predicted without making additional model studies.
2. The design procedure has been generalized.
3. The size of the stilling basin has been reduced to the minimum that will assure protection to the structure and prevent excessive erosion in the downstream channel.
4. The SAF stilling basin is very economical to construct.
5. Use of the SAF stilling basin under actual field conditions has demonstrated its effectiveness and has verified the predictions based on the laboratory tests.

A design chart, giving the proportions of the SAF stilling basin and the design equations and graphical solution of these equations, is presented on the center fold, pages 8 and 9.

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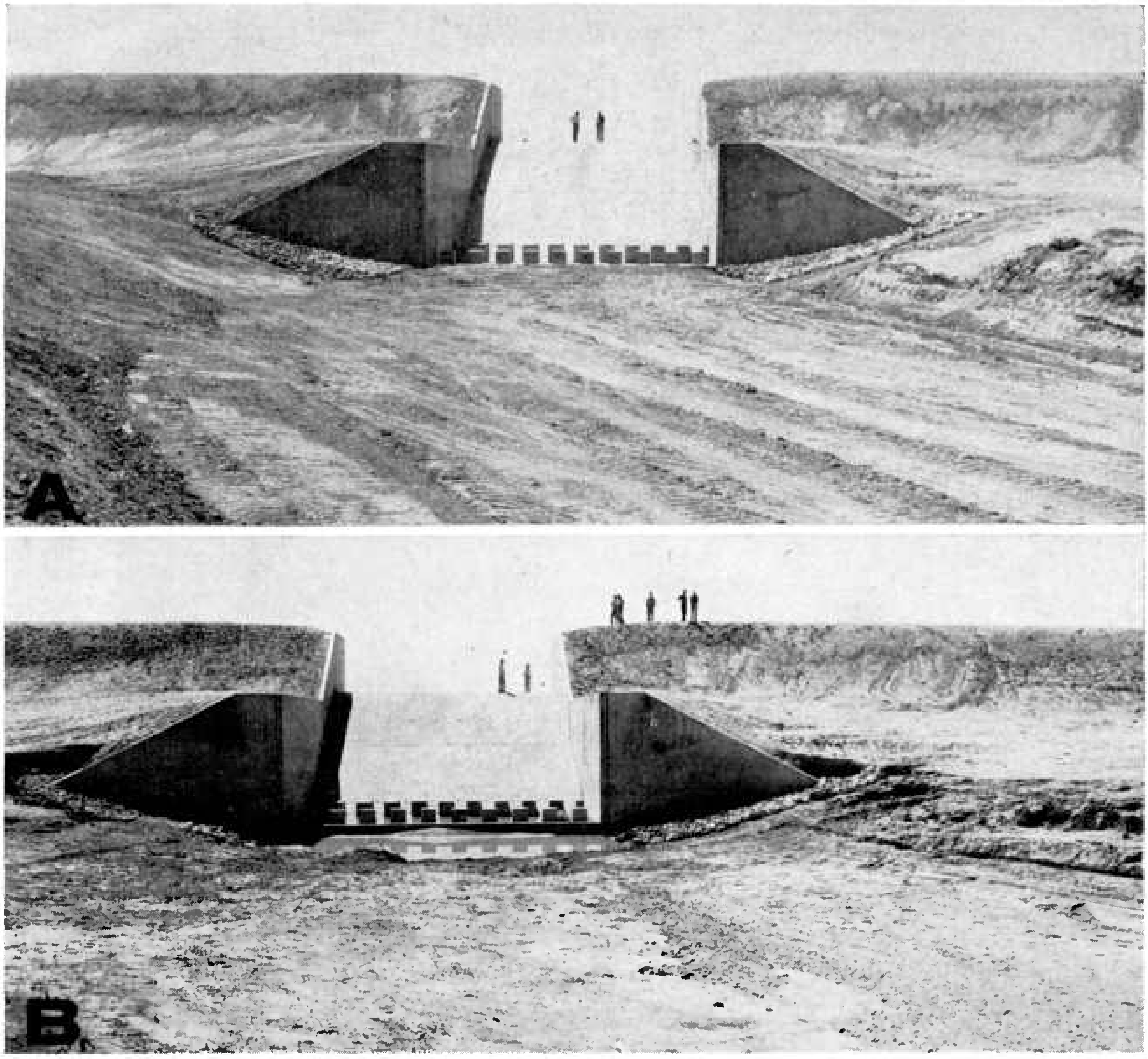

FIGURE 5.—San Simon drop structure—Spillway crest elevation is 88 feet; dam crest elevation, 103; end sill elevation, 68; chute, 40 feet wide; and stilling basin sidewalls, 18 feet high: *A*, After completion of structure, July 10, 1955; and *B*, after flow of 2,200 c. f. s., September 26, 1955.

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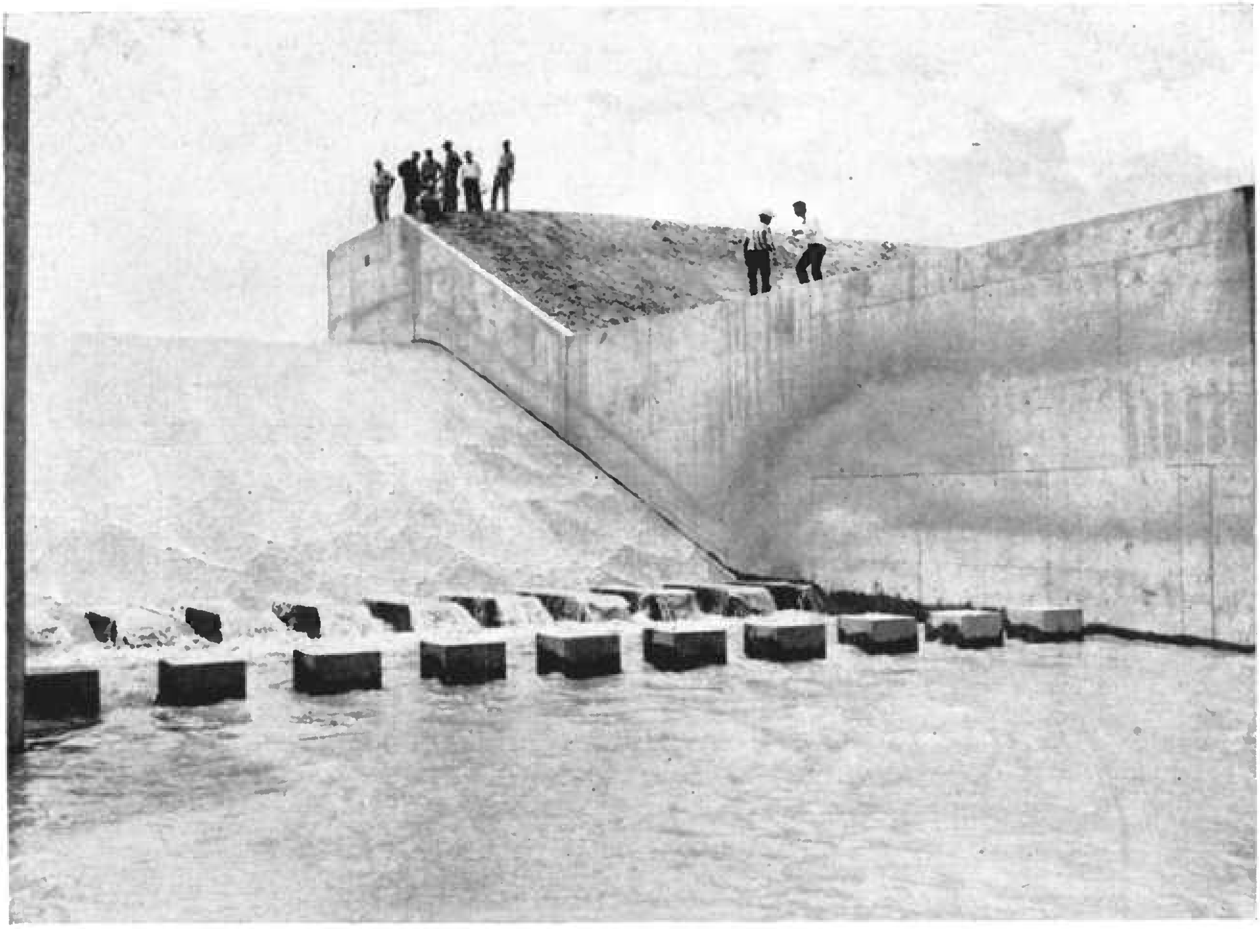

FIGURE 6.—Mud deposit on sidewalls of San Simon drop structure. The maximum flow line is 13 feet above the stilling basin floor, and the maximum splash line is about 16 feet above the basin floor. Photographed August 10, 1955.

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