HYDRAULIC MODEL STUDIES OF ST. ANTHONY FALLS SPILLWAY

by

St. Anthony Falls Hydraulic Laboratory
University of Minnesota

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Submitted by

LORENZ G. STRAUB

Director

Prepared by

SIGURD H. ANDERSON

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C O N T E N T S

L I S T   O F   F I G U R E S

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I. INTRODUCTION

In the spring of 1952, the maximum measured discharge of the Mississippi River occurred at the St. Anthony Falls dam of the Northern States Power Company at Minneapolis, Minnesota. As a result of this high flow, considerable damage was done to the spillway surface and to the rock-filled crib supporting the structure. These model tests were initiated by the Northern States Power Company to determine a hydraulic design for a structure to replace the damaged spillway. Because of continued high flow it has been impossible to complete a survey of the stream bed below the crest of the spillway. Therefore, the testing program has been limited to exploring the use of a previously developed design for a stilling basin.

The St. Anthony Falls spillway serves the purpose of conducting flood waters of the Mississippi River over St. Anthony Falls. The present structure is a wood plank surface supported on a rock-filled crib. The spillway is 425 ft wide, sloping at an angle of 12° from the crest situated at elevation 785.2 ft MSL. The downstream portion is a concave curve tangent in elevation to the slope and a horizontal line at elevation 749.6 ft MSL. The overall length of the spillway is 245 ft. The profile of the present structure is shown in Fig. 4.

Mr. G. E. Loughland, Engineering Consultant for the Northern States Power Company, requested that a general stilling basin design known as the SAF* stilling basin, developed by the Soil Conservation Service,[1, 2] be tested to ascertain its usefulness for this project. Two models of the SAF design were constructed, tested, and compared with the action of the existing spillway structure.

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*St. Anthony Falls.

[1] F. W. Blaisdell. "The SAF Stilling Basin," SCS-TP-79 (1949).

[2] F. W. Blaisdell, "Development and Hydraulic Design, SAF Stilling Basin," Transactions, American Society of Civil Engineers, Vol. 113, p. 483 (1948).

II. HYDRAULIC MODEL DESIGNS

An analysis of the physical forces involved in the flow of water over a spillway shows that gravity is the predominant force; therefore the model must be operated in accordance with the Froude Model Law. Once the ratio of model to prototype has been fixed, scale ratios necessary for similarity are determined. After consideration of the available testing equipment, a scale ratio of 1:58.6 was adopted. Using this scale ratio, the following ratios are obtained:

Quantity	Ratio - Model to Prototype
Length	1:58.6
Area	1:3434
Velocities	1:7.65
Discharge	1:26,290
Pressures	1:58.6

The models were to be tested in a glass-walled channel 6 in. wide. Therefore, the section represented 6.9 per cent of the total width of the main spillway (425 ft) or a crest length of 29.3 ft.

The model discharge was computed as

$$Q_m = \frac{.069 \times \text{the design of discharge}}{26,290}$$

Three design discharges were used:

Prototype Discharge - Q_p	Model Discharge - Q_m
50,000 cfs	0.131 cfs
80,000 cfs	0.210 cfs
100,000 cfs	0.262 cfs

The tailwater elevations are controlled by the lower dam of St. Anthony Falls. The pool elevations to be maintained by the lower dam, as given by the St. Paul District Office of the Corps of Engineers, U. S. Army, will be as follows:

Discharge	Lower Pool Elevation
0 - 65,000 cfs	750 ft MSL
65,000 - 73,000 cfs	751.7 ft MSL
100,000 cfs	756 ft MSL

A. SAF Stilling Basin Design

The actual design of the SAF stilling basin model was based on information contained in the SAF stilling basin design manual.* The only quantities required for the design are the depth and velocity of the approaching stream of water. The velocity can be determined, within reasonable limits, by knowing the difference in elevation between the upper pool and the approximate elevation of the flow directly above the stilling basin. Neglecting the velocity of approach, the upper pool elevation can be approximated by

$$\text{upper pool elevation} = \text{crest elevation} + \frac{3}{2}\, d_c$$

where

$$d_c = \left(\frac{Q^2}{b^2 g}\right)^{1/3}$$

and

Q = design discharge in cfs

b = width of channel or crest length in ft

g = acceleration due to gravity in sq ft per sec

The elevation of the water surface in the chute at the point where it enters the stilling basin can be approximated by trial by considering the tailwater elevation to be the sequent depth of the hydraulic jump. Then

h = upper pool elevation − tailwater elevation,

$$v_1 = \sqrt{2 g h}$$

and

$$d_1 = \frac{Q}{b v_1}$$

where v_1 = velocity of water entering the stilling basin and d_1 = depth of water entering the stilling basin.

With these data, the dimensions of the stilling basin for each design flood can be taken directly from the design manual. The dimensions of a SAF stilling basin for design discharges of 50,000, 80,000, and 100,000 cfs, computed by methods of the design manual (p. 13), are tabulated as follows:

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*See Footnote 1.

Table I

PROPERTIES OF SAF STILLING BASIN FOR VARIOUS DESIGN FLOODS

Item	Design Discharge cfs		
	50,000	80,000	100,000
Critical depth - d_c	7.53	10.30	11.95
Upper pool elevation	796.5	800.6	803
Tailwater elevation	750	751.7	756
Water surface elevation entering basin	735	737	739
Head - h	61.5	63.6	64
Velocity entering basin - v_1	62.8	63.9	64.1
Depth - d_1	1.87	2.95	3.67
Froude number - F_1	65.5	42.1	34.7
Theoretical tailwater depth - d_2	23	25	27
Actual tailwater depth - d'_2	17.5	22	26
Height of end sill	1.22	1.54	1.9
Length of stilling basin - L_b	22	27	32
Width and spacing of blocks	1.87	2.96	3.67
Slope of chute (arbitrary)	30°	30°	30°
Elevation of stilling basin floor	732.5	732.5	732.5

The design manual recommends that the floor blocks occupy an area of from 40 to 55 per cent of the width of the stilling basin. The width and spacing of the blocks for this study were arbitrarily selected to equal d_1 and resulted in an occupied width of 50 per cent of the stilling basin width. A sectional view of this design for the discharge of 100,000 cfs is shown in Fig. 1.

B. Description of the Model

The model tests were performed at the Experimental Engineering Laboratories of the University of Minnesota. A glass-walled channel 6 in. wide and 16 in. deep, equipped with flow metering and tailwater control devices, was available for testing without any alterations or additional equipment. This unit included a previously calibrated orifice-meter for determining discharge rates. A centrifugal pump supplied water to a constant level tank from which a metered flow was obtained for the test channel. The model was fabricated of Lucite sheet stock. Tailwater depths were controlled by an adjustable sluice gate and their elevations determined by a point gage to the nearest 0.01 in. or approximately to within 1/2 in. prototype.

C. Movable Bed Sediment

Preliminary tests of an existing SAF stilling basin designed for approximately 50,000 cfs, as shown in Fig. 2, indicated that a movable bed consisting of silica blast sand of 0.02 in. average diameter (Fig. 3), would be satisfactory for purposes of these tests. However, when the model of the original spillway surface (Fig. 4) was placed in operation, it was evident that a coarser material would be required. Consequently, for the Series II and IV test runs, a gravel of average size (approximately 1/2 inch in diameter) was used (Fig. 3). This material furnished a very good comparison between the scour pattern of the original spillway model and the SAF design for 100,000 cfs. Photographs of Runs 5, 6, and 6A, as compared with Runs 13, 14, and 15, show clearly that considerable bed movement occurred in the original design whereas no movement was observed in the SAF design.

III. TEST OPERATIONS

The testing procedure was as follows: The movable bed below the model was brought to the proper elevation in accordance with soundings obtained from the survey of the river bed made by the Corps of Engineers in 1938. The design discharge was then set by the orifice-meter and the tailwater adjusted until the required tailwater elevation was obtained. The test was continued until a stabilized scour pattern had developed below the stilling basin. In most instances the length of run was from 45 min to 1 hour. However, the test of the original spillway, using the silica blast sand in the movable bed, was limited to a few minutes because incomplete energy dissipation by the structure would have caused removal of all the bed material. Photographic records of each run were made viewing the stilling basin through a grid system divided at 5-ft intervals vertically and 10-ft distances horizontally.

IV. PRESENTATION OF TEST RESULTS

Series I

The first series, exploratory in nature, was made on an existing SAF stilling basin model (Fig. 2). Although constructed for another purpose, this model was dimensioned for a flow of 50,000 cfs, except that the length of basin was 17 ft instead of 22 ft as specified in the SAF design manual. Three test runs were made on this model with silica blast sand used as a bed material. Photographic records of the scour pattern for each run are shown in Fig. 6.

Run No. 1: With a discharge of 50,000 cfs, the stilling basin appears to have fairly good energy dissipation. The scour hole did not go below elevation 730 ft MSL.

Run No. 2: Discharge through structure was 80,000 cfs. This run shows that the apron is too short and that the jump takes place off the end of the apron. Depth of scour appears to be about 10 ft below apron level.

Run No. 3: This discharge is 100,000 cfs or 100 per cent over the design flow. The length of the scour hole has increased and has scoured to the bottom of the channel. The jump is well off the end of the stilling basin, and the water surface is very rough. This flow is definitely beyond the capacity of this stilling basin.

Series II

The second series was made on the original spillway model with pea rock (average diameter 1/2 in.) for bed material. The channel below the apron was placed at elevations given by stream bed soundings, but the force of the jet quickly formed the scour hole as shown by the photographs of Runs 5, 6, and 6A. After the initial movement had taken place, only minor changes in the scour hole occurred. Individual gravel particles were shifted within the limits of the hole, but the pattern of the bed remained unchanged. Photographs of the scour pattern for this series are shown in Fig. 7.

Run No. 5: Discharge 50,000 cfs. Erosion of bed to elevation 725 ft MSL. Stream unable to move material removed from scour hole and deposited at Sta. 1 + 60. Time of run 1 hour.

Run No. 6: Discharge 80,000 cfs. Scour hole lengthened with considerable movement of material within area of scour. Time of run 1 hour.

Run No. 6A: Discharge 100,000 cfs. Length of scour hole further increased. Material shifted along bottom of scoured area. No movement of bed after 150 ft below end of apron. Time of run 1 hour.

Series III

This series was made with a model of the original spillway from the crest to the end of the apron (Fig. 4). The bed material selected for this series, as for Series I, was silica blast sand. The photographs of Runs 7, 8, and 9 show that this material was too erosive for use with this model.

Run No. 7: Discharge 50,000 cfs. Jet scours deep hole in bed. Time of run 12 minutes.

Run No. 8: Flow of 80,000 cfs enlarges scour hole and extends effect of jet farther downstream. Time of run 10 minutes.

Run No. 9: This is for maximum design flow of 100,000 cfs. The jump below the apron is very unstable and caused the scour seen in the photograph in a run of 3 min duration.

Series IV

A SAF stilling basin designed for a maximum discharge of 100,000 cfs was tested in this series of runs. Flows of 50,000 cfs and 80,000 cfs were also used to determine the effect of the operation of the stilling basin at discharges less than the design flow. The bed material used was pea rock, the same material used in Series II.

Run No. 13: Discharge 100,000 cfs. No movement of the bed, and comparatively smooth water surface directly below stilling basin. This is the design flow.

Run No. 14: Discharge 80,000 cfs. No movement of the bed. Jump inside limits of stilling basin.

Run No. 15: Discharge 50,000 cfs. No movement of the bed.

Series V

The test conditions for this series of runs were identical with those of Series IV except that silica blast sand was used in these runs to provide a bed material which would readily show any tendency, however slight, towards erosion below the end sill.

Run No. 16: Discharge 50,000 cfs. The jump appears to be fully contained on the stilling basin. The scour hole does not go below elevation 726 ft MSL.

Run No. 17: Discharge 80,000 cfs. The scour hole is slightly deeper and longer than for Run No. 16, but the action of the stilling basin is very good.

Run No. 18: Discharge 100,000 cfs. The scour hole for this run is somewhat longer than for Runs 16 and 17 but is not noticeably deeper. The jump appears to be contained on the stilling basin floor.

V. DISCUSSION OF TEST RESULTS

A comparison of the photographic records of Series II and IV and Series III and V clearly reveals the effectiveness of the SAF design as compared with the original spillway apron. Not only is the erosive force of the jet almost completely eliminated, but the extent of the action of the hydraulic jump is reduced so that the water surface below the stilling basin is quite calm. The Series V tests show that even when the bed material used is quite fine, the stilling basin is still effective in controlling erosion. The lower dam, situated a short distance downstream from the St. Anthony spillway, will provide control of the tailwater elevations, a factor which, together with the probable foundation conditions, is favorable to the SAF type of stilling basin. Another factor in its favor is the relatively short length of the stilling basin.

In these experiments the effect of floating debris, such as ice, on the operation or the structural stability of the stilling basin was not considered. Further study would be required to evaluate the importance of this aspect.

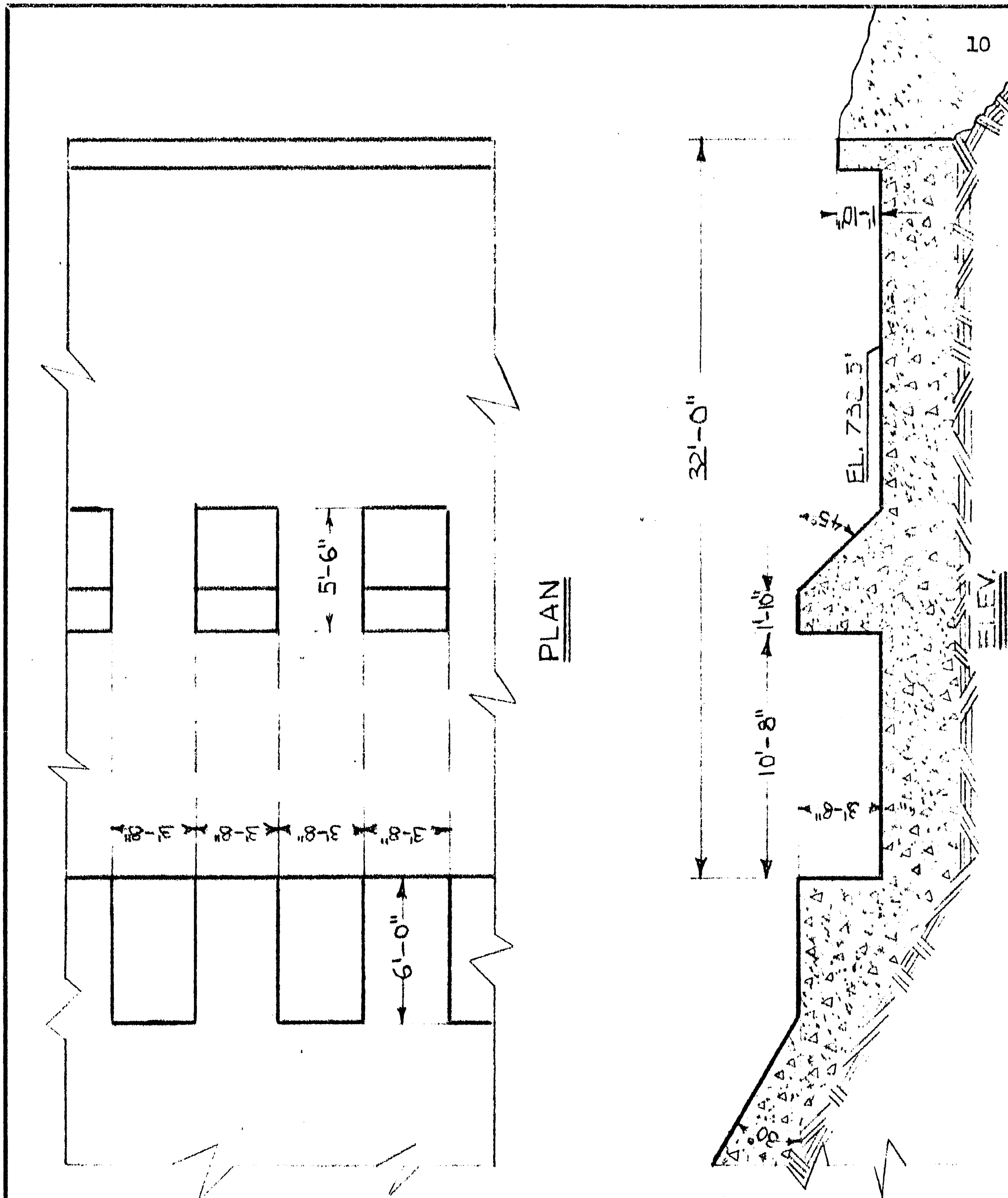
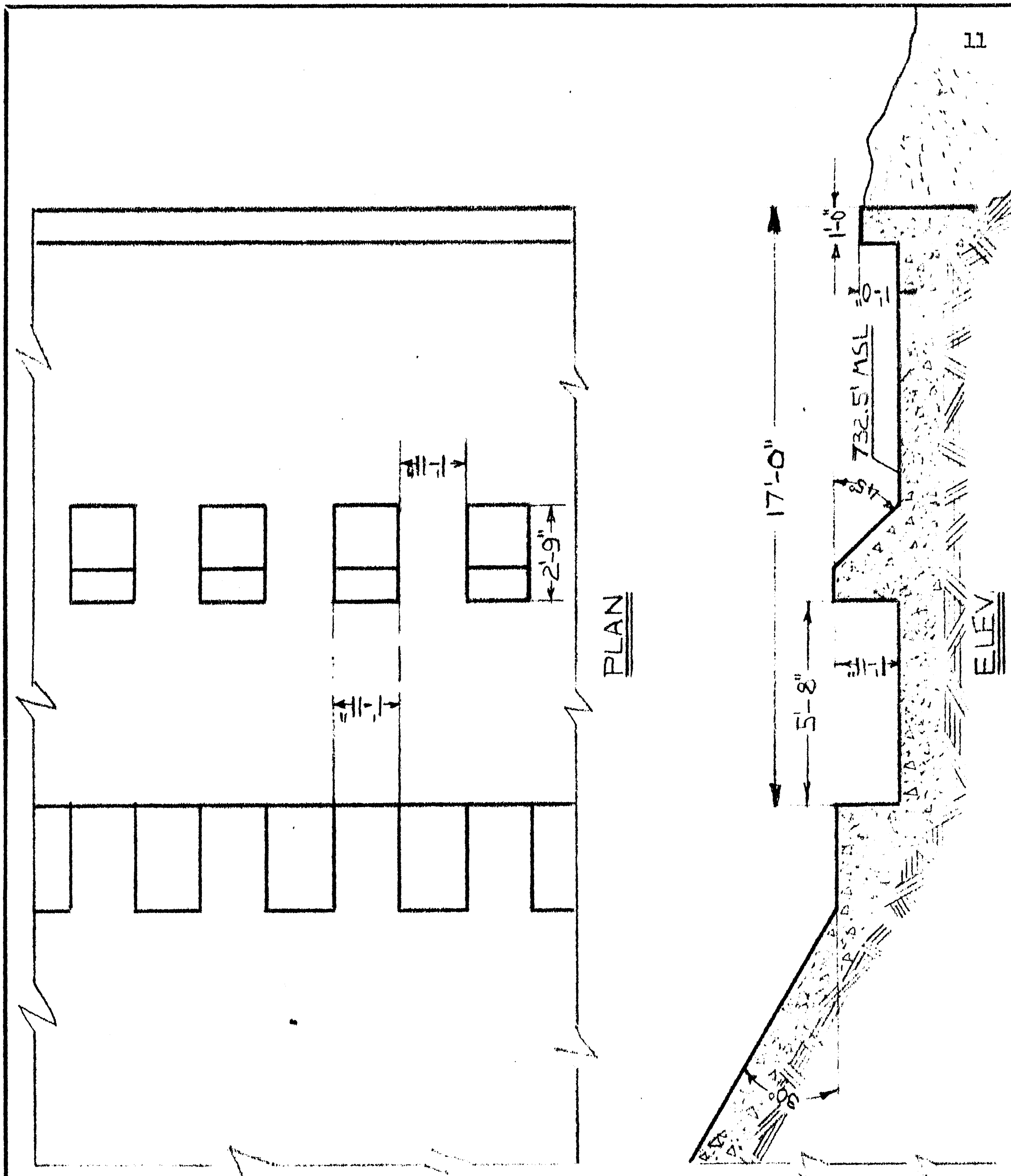


FIG. 1

ST. ANTHONY FALLS SPILLWAY
SAF DESIGN FOR 100.000 CPS
BLOCK AND SILL LOCATION
MODEL SCALE 1:52.6

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN BY SHA	CHECKED BY	APPROVED
SCALE 1" = 6'-0"	DATE 7-21-52	DRAW. NO.



ST. ANTHONY FALLS SPILLWAY
SAF DESIGN FOR 50,000 CFS
BLOCK AND SILL LOCATION
MODEL SCALE 1:58.6

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN BY SHA	CHECKED BY	APPROVED
SCALE 1" = 4'-0"	DATE 7-22-52	DRAW. NO.

FIG. 2

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA
SEDIMENT SIZE DISTRIBUTION

Tested by: ____________

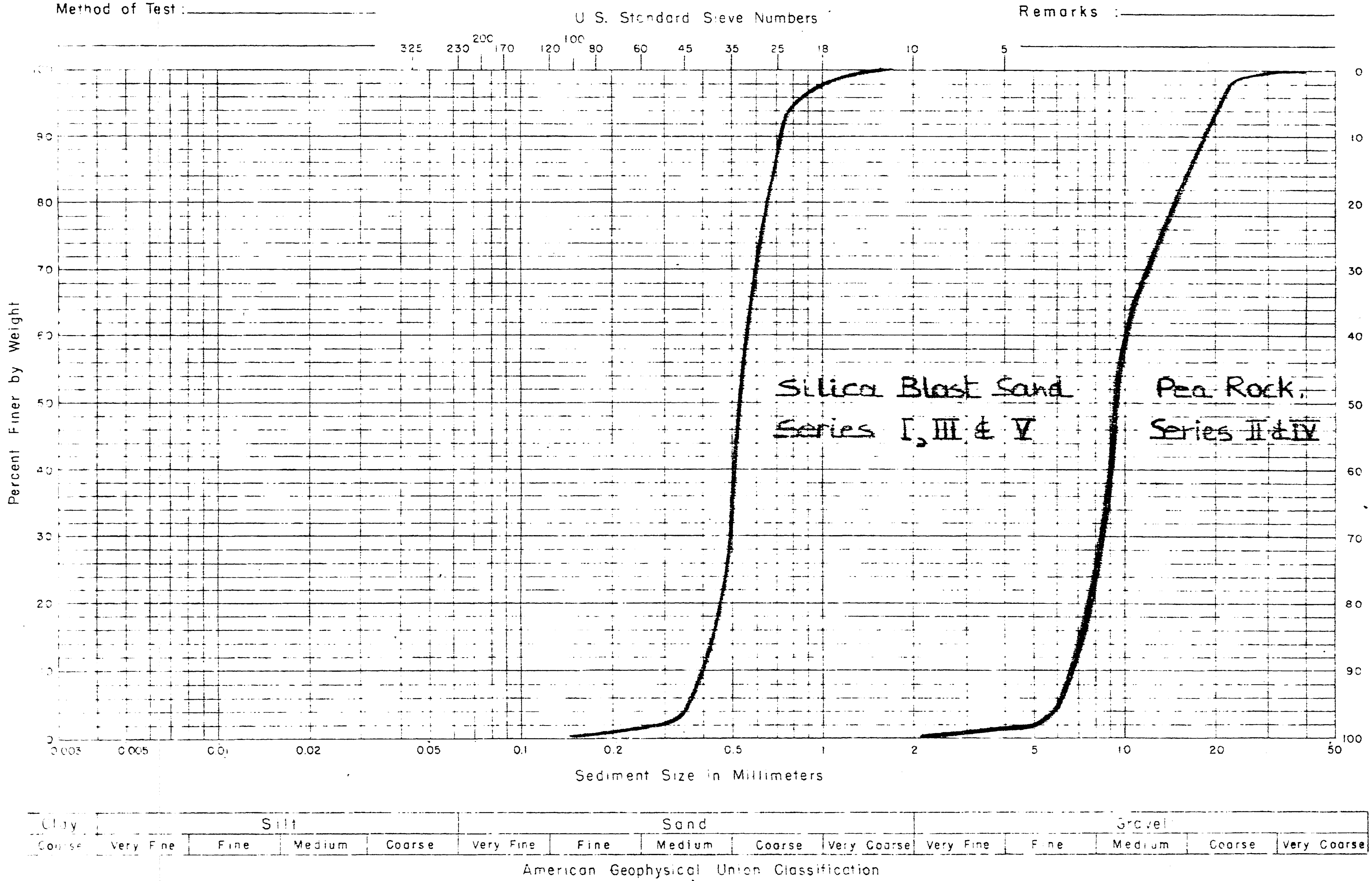
Date of Test: ____________

Method of Test: ____________

Serial No. ____________

Source: ____________

Remarks: ____________



Bed Sediment used in Experiments

FIG. 3

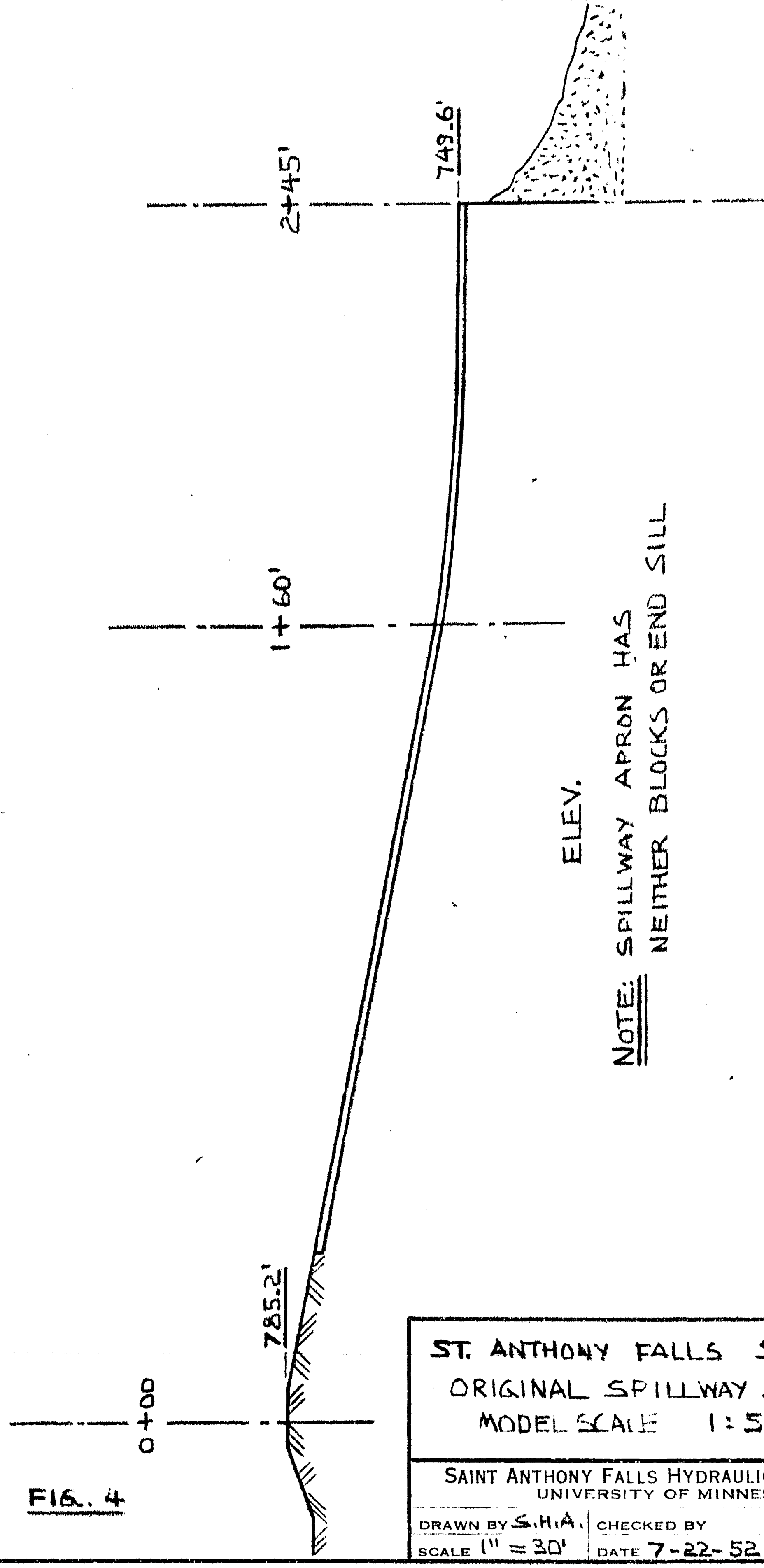


FIG. 4

ST. ANTHONY FALLS SPILLWAY
ORIGINAL SPILLWAY SURFACE
MODEL SCALE 1:58.6

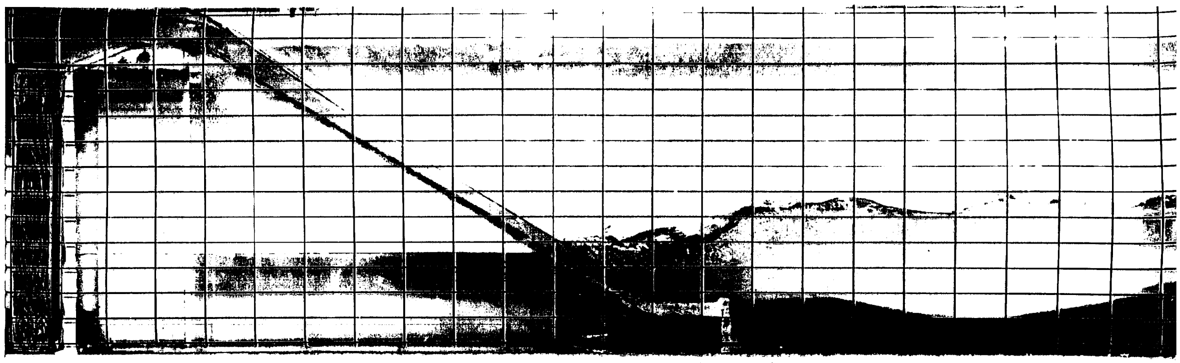
SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN BY S.H.A.	CHECKED BY	APPROVED
SCALE 1" = 30'	DATE 7-22-52	DRAW. NO.

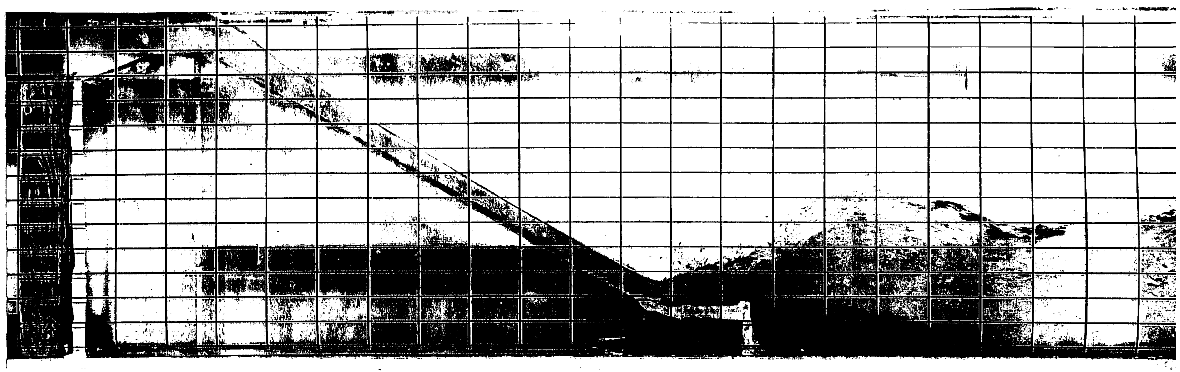
ST. ANTHONY FALLS SPILLWAY STUDIES - SERIES I

SAF Design for 50,000 cfs
Stilling Basin Elev. - 732.5 ft MSL

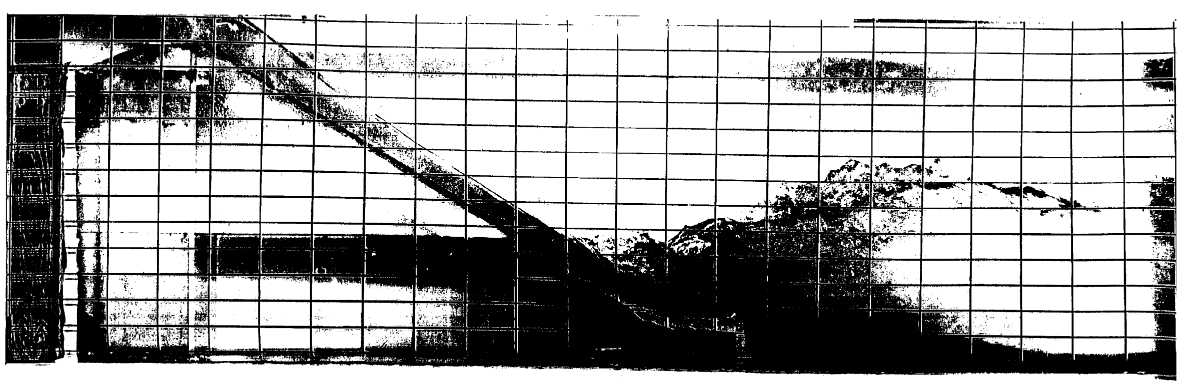
Model Scale - 1:58.6
Bed Material - Silica Blast Sand



Run No. 1: Discharge - 50,000 cfs
Tailwater Elev. - 750 ft MSL
Duration - 45 min.
Photo 2930



Run No. 2: Discharge - 80,000 cfs
Tailwater Elev. - 751.7 ft MSL
Duration - 40 min.
Photo 2931



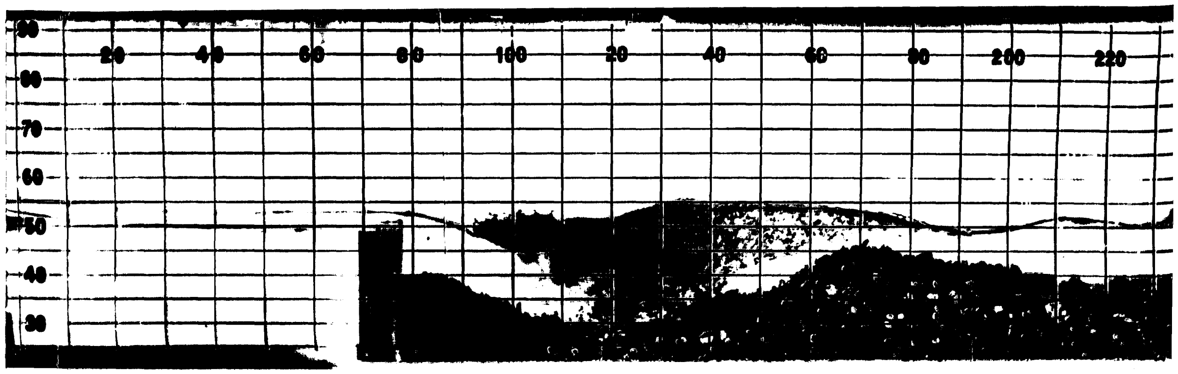
Run No. 3: Discharge - 100,000 cfs
Tailwater Elev. - 756 ft MSL
Duration - 30 min.
Photo 2932

Fig. 5 - **Erosion** Pattern - Series I

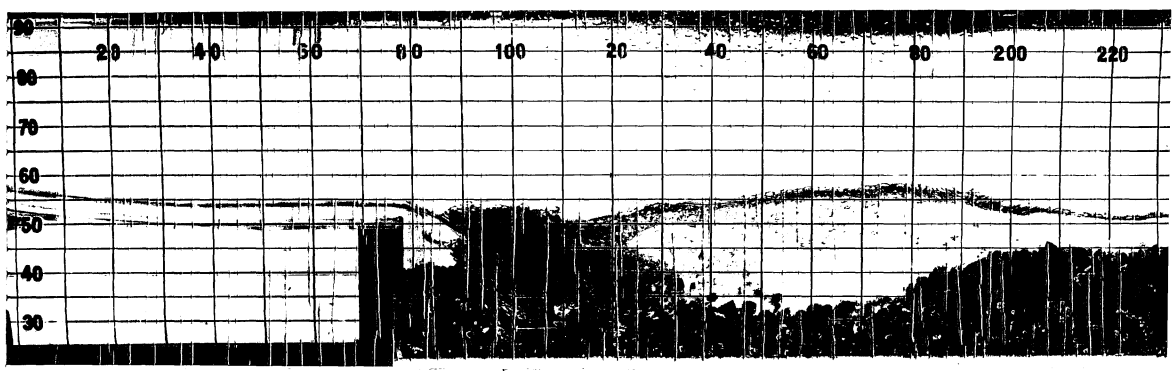
ST. ANTHONY FALLS SPILLWAY STUDIES - SERIES II

Original Spillway Profile
Spillway Apron Elev. - 749.6 ft MSL

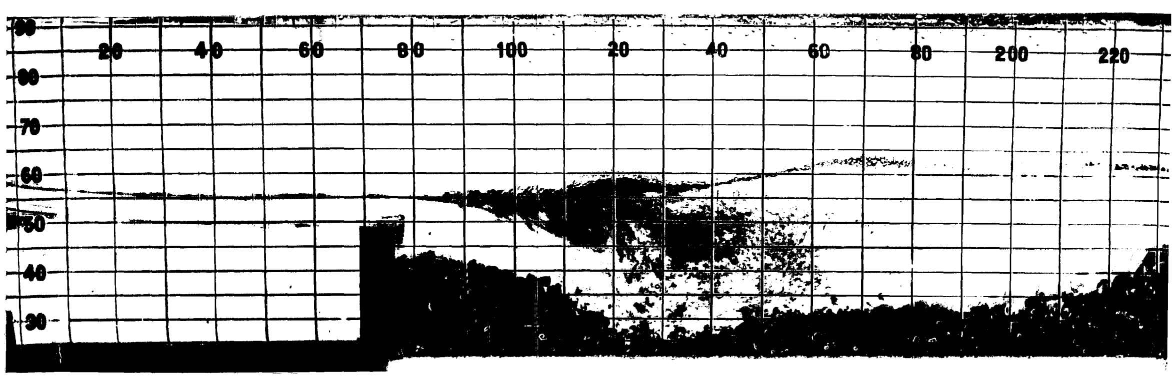
Model Scale - 1:58.6
Bed Material - Pea Rock



Run No. 5: Discharge - 50,000 cfs
Tailwater Elev. - 750 ft MSL
Duration - 1 hour
Photo 2936



Run No. 6: Discharge - 80,000 cfs
Tailwater Elev. - 751.7 ft MSL
Duration - 1 hour
Photo 2937



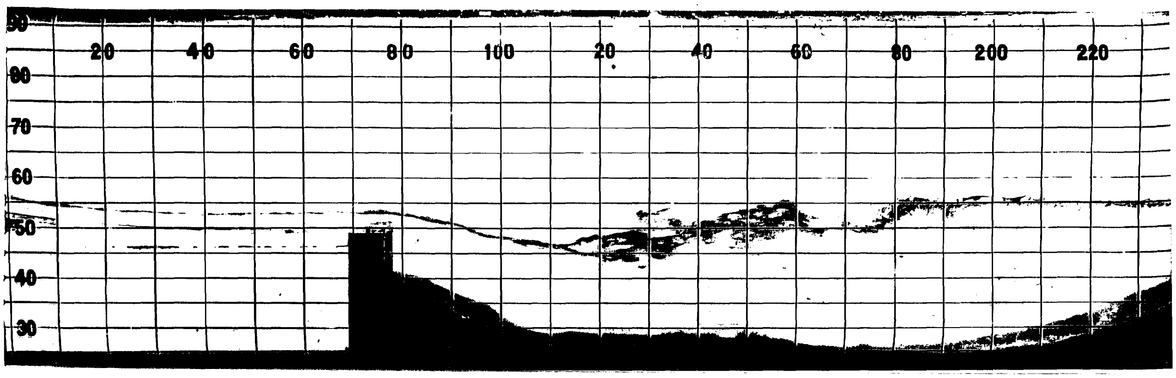
Run No. 6A: Discharge - 100,000 cfs
Tailwater Elev. - 756 ft MSL
Duration - 1 hour
Photo 2947

Fig. 6 - Erosion Pattern - Series II

ST. ANTHONY FALLS SPILLWAY STUDIES - SERIES III

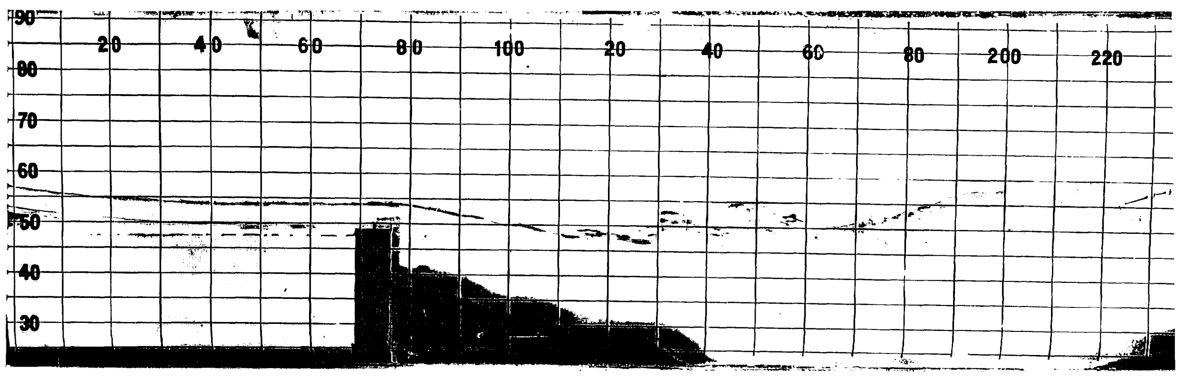
Original Spillway Profile
Spillway Apron Elev. - 749.6 ft MSL

Model Scale - 1:58.6
Bed Material - Silica Blast San



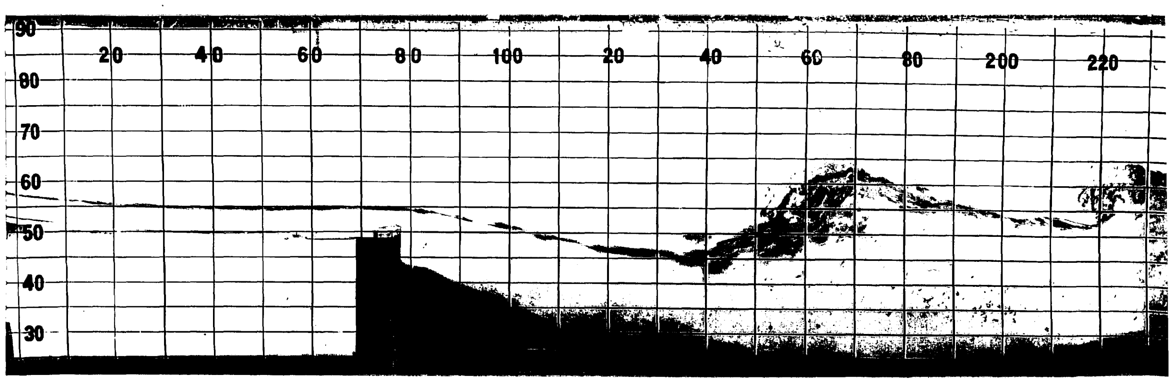
Run No. 7: Discharge - 50,000 cfs
Tailwater Elev. - 750 ft MSL

Duration - 12 min.
Photo 2938



Run No. 8: Discharge - 80,000 cfs
Tailwater Elev. - 751.7 ft MSL

Duration - 10 min.
Photo 2939



Run No. 9: Discharge - 100,000 cfs
Tailwater Elev. - 756 ft MSL

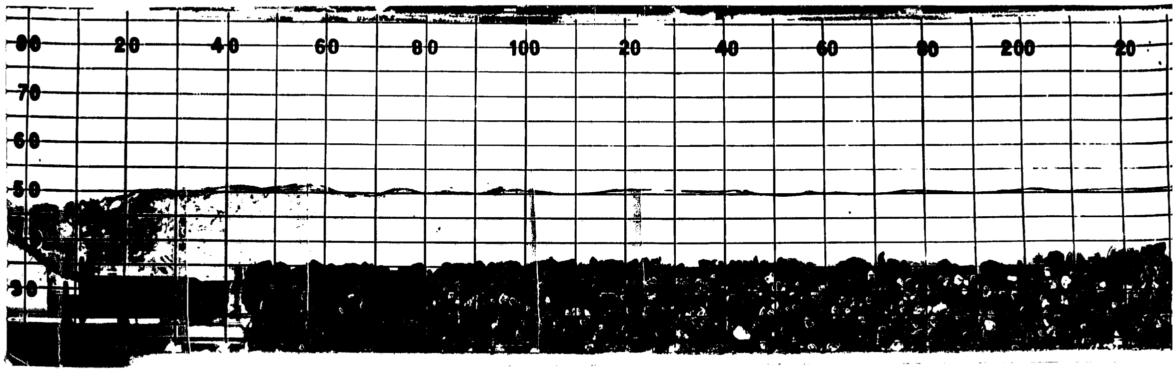
Duration - 3 min.
Photo 2940

Fig. 7 - Erosion Pattern - Series III

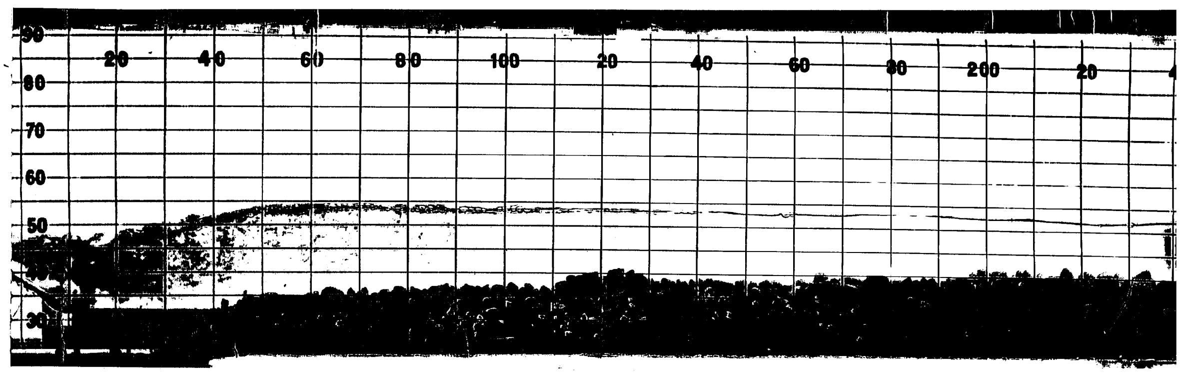
ST. ANTHONY FALLS SPILLWAY STUDIES - SERIES IV

SAF Design for 100,000 cfs
Stilling Basin Elev. - 732.5 ft MSL

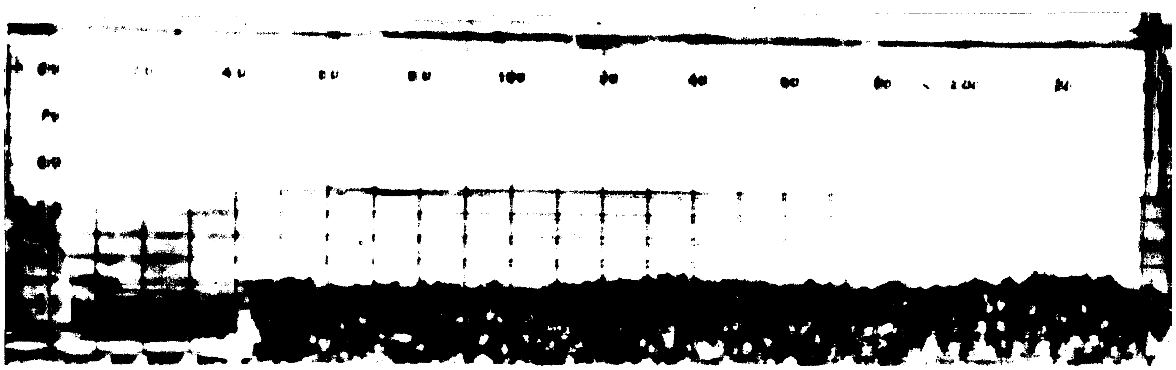
Model Scale - 1:58.6
Bed Material - Pea Rock



Run No. 15: Discharge - 50,000 cfs
Tailwater Elev. - 750 ft MSL
Duration - 1 hour
Photo 2946



Run No. 14: Discharge - 80,000 cfs
Tailwater Elev. - 751.7 ft MSL
Duration - 1 hour
Photo 2945



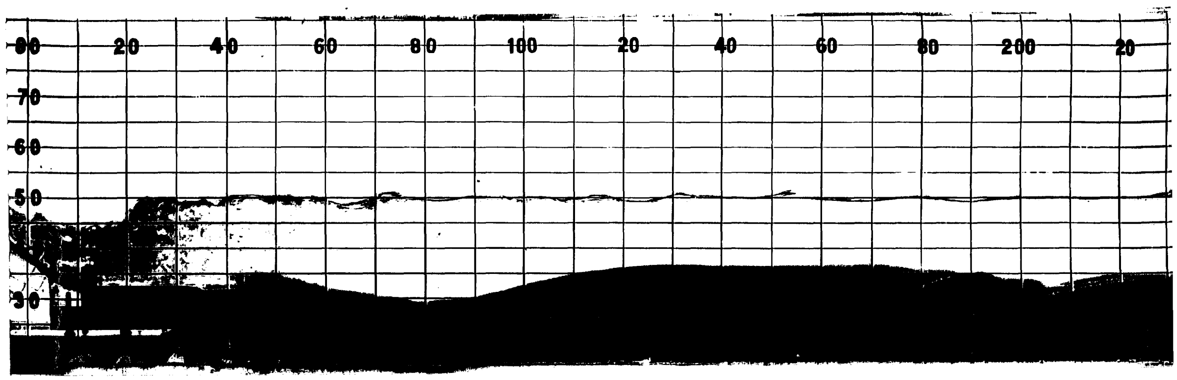
Run No. 13: Discharge - 100,000 cfs
Tailwater Elev. - 756 ft MSL
Duration - 1 hour
Photo 2944

Fig. 8 - Erosion Pattern - Series IV

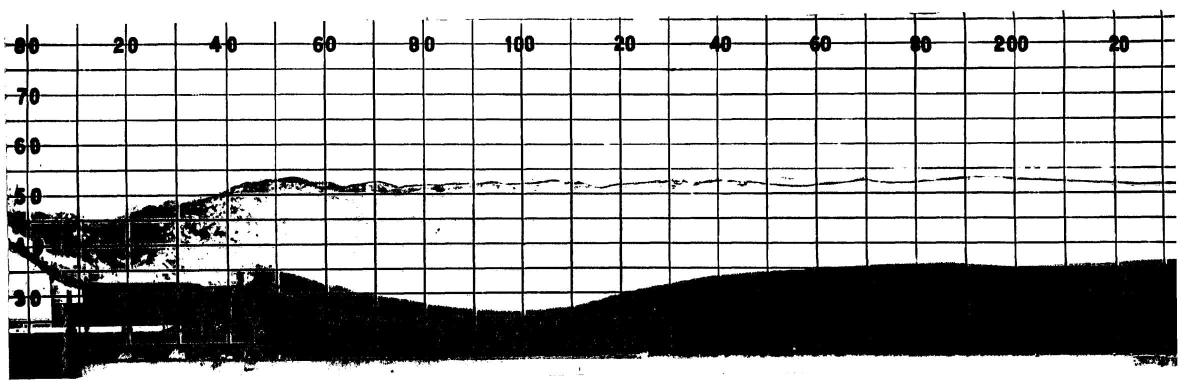
ST. ANTHONY FALLS SPILLWAY STUDIES - SERIES V

SAF Design for 100,000 cfs
Stilling Basin Elev. - 732.5 ft MSL

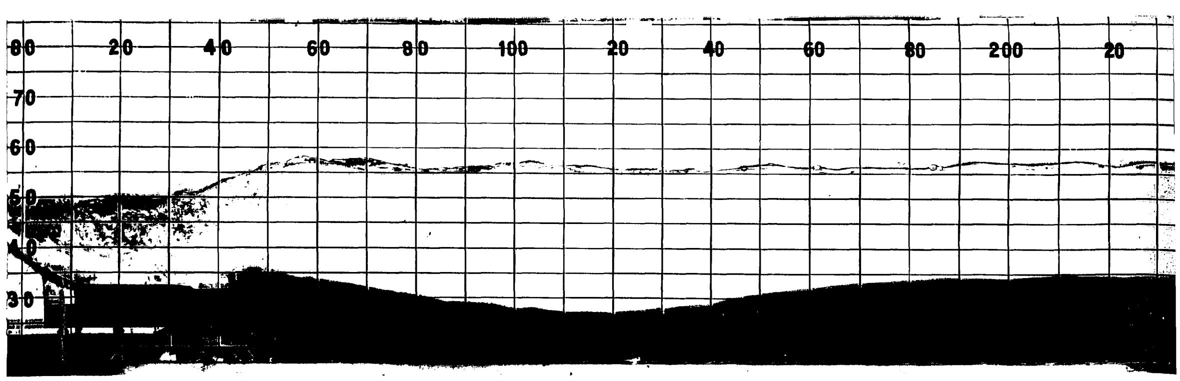
Model Scale - 1:58.6
Bed Material - Silica Blast Sand



Run No. 16: Discharge - 50,000 cfs
Tailwater Elev. - 750 ft MSL
Duration - 45 min.
Photo 2941



Run No. 17: Discharge - 80,000 cfs
Tailwater Elev. - 751.7 ft MSL
Duration - 45 min.
Photo 2942



Run No. 18: Discharge - 100,000 cfs
Tailwater Elev. - 756 ft MSL
Duration - 45 min.
Photo 2943

Fig. 9 - Erosion Pattern - Series V