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Model study of ninety degree spillway for nockamixon dam, March 1967

D. R. Basco

J. B. Herbich

P. D. Erfle

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MODEL STUDY OF NINETY DEGREE SPILLWAY FOR NOCKAMIXON DAM

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by
David R. Basco
John B. Herbich
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Fritz Engineering Laboratory Report No. 326.2

LEHIGH UNIVERSITY
CIVIL ENGINEERING DEPARTMENT
FRITZ ENGINEERING LABORATORY
HYDRAULIC AND SANITARY ENGINEERING DIVISION

MODEL STUDY OF NINETY DEGREE SPILLWAY
FOR
NOCKAMIXON DAM

Project Report No. 52

Prepared by

David R. Basco

John B. Herbich

and

Paul D. Erfle

Prepared for

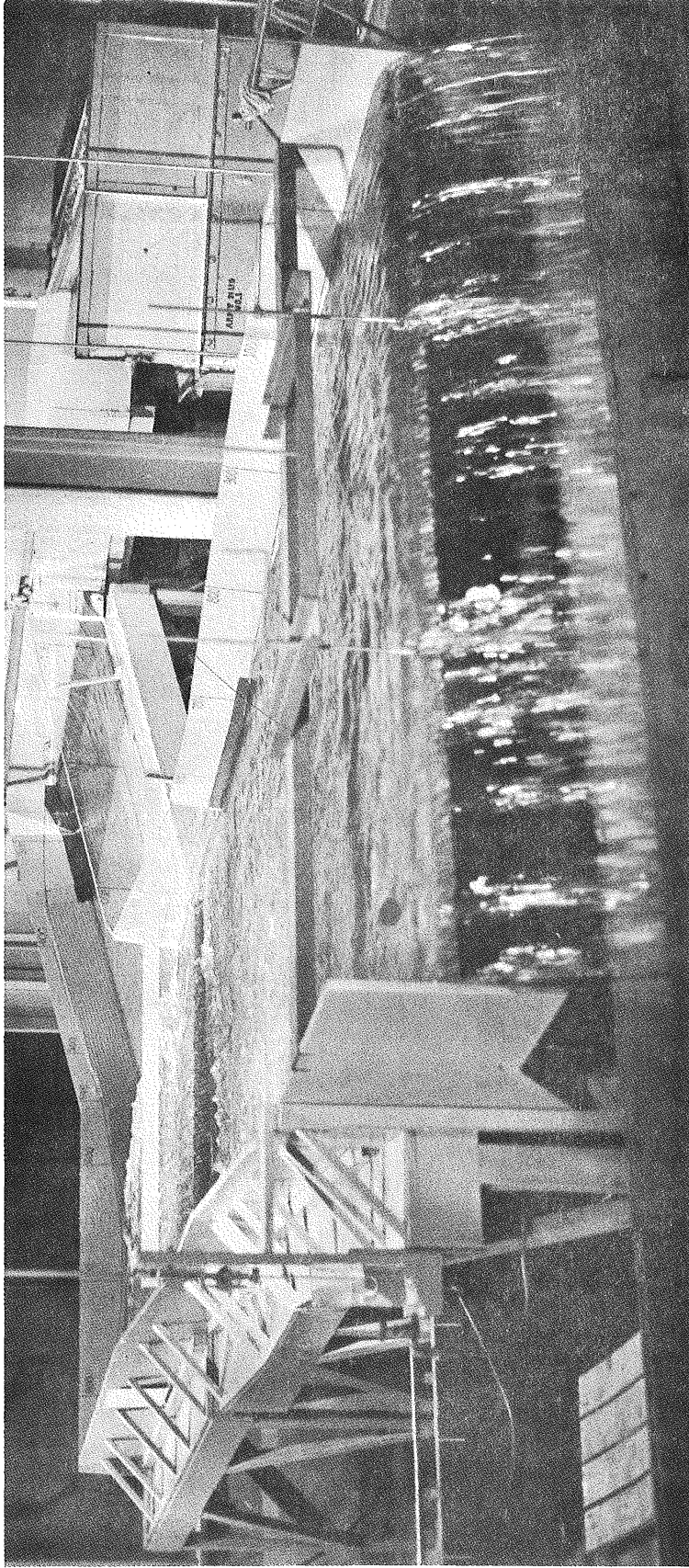
The General State Authority

Harrisburg, Pennsylvania

March, 1967

Bethlehem, Pennsylvania

Fritz Engineering Laboratory Report No. 326.2



Laboratory Model With Original Spillway Configuration

A B S T R A C T

A hydraulic model study of an unusually designed spillway was requested by the General State Authority, Commonwealth of Pennsylvania. The dam is to be located in Bucks County, Pennsylvania and is part of "Project 70" designed to increase the number of recreational facilities in the Commonwealth. Economics and the topography at the dam site dictated the ninety degree turn in the spillway.

A 60 to 1 scale model was constructed in the Hydraulics Laboratory, Civil Engineering Department, Lehigh University. The Consulting Engineers' original design was tested and it was found that several improvements in the hydraulic flow patterns should be made. The flows over the control weirs, energy dissipators (hydraulic jumps) and flow passages were all in need of hydraulic improvement. Modifications made to the model primarily consisted of improving entrance conditions to the first weir by use of a large streamlined dike; rounding the corners of the ninety degree turn to provide smoother flow; and redesigning the second weir to produce a more efficient hydraulic jump. All modifications resulted in totally improved flow patterns and energy dissipation in the entire spillway structure. The model study also resulted in some cost saving in construction which more than offset the cost of the model study.

A B S T R A C T (continued)

It was therefore concluded that if the prototype spillway is constructed according to the final design as determined by the model study, the dam will adequately be protected from the Standard Project Flood for the drainage basin.

P R E F A C E

A research contract between the General State Authority, Commonwealth of Pennsylvania, Harrisburg, Pennsylvania and Lehigh University's Institute of Research provided for experimental hydraulic studies of an unusually designed right angle spillway. Pickering, Corts and Summerson, Inc., Consulting Engineers, Langhorne, Pennsylvania, are responsible for the design of Project No. G.S.A. 194-12, Nockamixon State Park, Bucks County, Pennsylvania. Justin and Courtney, Consulting Engineers, Philadelphia, Pennsylvania, have been subcontracted for the dam and spillway design. The model investigation was conducted by the Hydraulic and Sanitary Engineering Division of Fritz Engineering Laboratory, Department of Civil Engineering.

The study was made on a dynamically similar model of the spillway and was primarily concerned with checking the hydraulic performance of the Consulting Engineer's uniquely arranged spillway design.

The project had been under the direction of Dr. John B. Herbich, who was *Chairman of the Hydraulics and Sanitary Engineering Division at Lehigh University. Dr. John R. Adams is currently Acting Chairman of

* Currently, Head of Hydraulic Engineering and Fluid Mechanics Division, Texas A & M University, College Station, Texas.

P R E F A C E (continued)

of the Division. Dr. Herbich was assisted by Mr. David R. Basco, Research Instructor and Mr. Paul D. Erfle, Research Assistant.

Dr. L. S. Beedle is Acting Head of the Department of Civil Engineering and Director of Fritz Engineering Laboratory.

T A B L E O F C O N T E N T S

	<u>Page</u>
ABSTRACT	i
PREFACE	iii
TABLE OF CONTENTS	v
LIST OF ILLUSTRATIONS, TABLES AND PHOTOGRAPHS	vii
I. INTRODUCTION	1
A. Purpose of Study	1
B. Model Scale	7
C. General Test Program	8
II. MODEL TEST FACILITY	9
A. Original Model Design	9
B. Modifications	15
1. Spillway	15
2. Forebay	18
III. INSTRUMENTATION	24
IV. THEORETICAL ANALYSIS	27
A. Model Laws	28
B. Channel Roughness	29
V. RESULTS OF STUDY	33
A. General	33
B. Lower Half Spillway	36
C. Weirs and Forebay	41

T A B L E O F C O N T E N T S (continued)

	<u>Page</u>
V. TEST RESULTS (continued)	
D. Miscellaneous Results	56
1. Retaining wall profile	56
2. Velocities	56
3. Channel Roughness	60
VI. SUMMARY OF RESULTS AND CONCLUSIONS	64
VII. ACKNOWLEDGMENTS	66
VIII. APPENDICES	67
A1 Lower Half Spillway - Contour Maps	68
A2 Weir Cross Sections	85
A3 References	107

LIST OF ILLUSTRATIONS,
TABLES, AND PHOTOGRAPHS

<u>Number</u>	<u>Title</u>	<u>Page</u>
Frontispiece	Laboratory Model with Original Spillway Configuration	
1	Location Plan	2
2	Drainage and Reservoir Areas	3
3	Proposed Spillway Design	5
4	Proposed Spillway Sections	6
5	Original Model Plan	10
6	Original Model Sections	11
7	Model Construction	12
8	Forebay Construction	14
9	Modified Spillway Plan	16
10	Modified Spillway Section	17
11	Original Forebay Plan and Sections	19
12	Original Forebay and First Weir Plan	20
13	Forebay Modification No. I	21
14	Forebay Modification No. II	22
15	Forebay Modification No. III - Final	23
16	8" x 5" Venturi Calibration	25
17	Model Test Data Table	34
18	Predicted Tailwater Rating Curve	35
19	First Jump at 100% Flowrate - Original Design	38

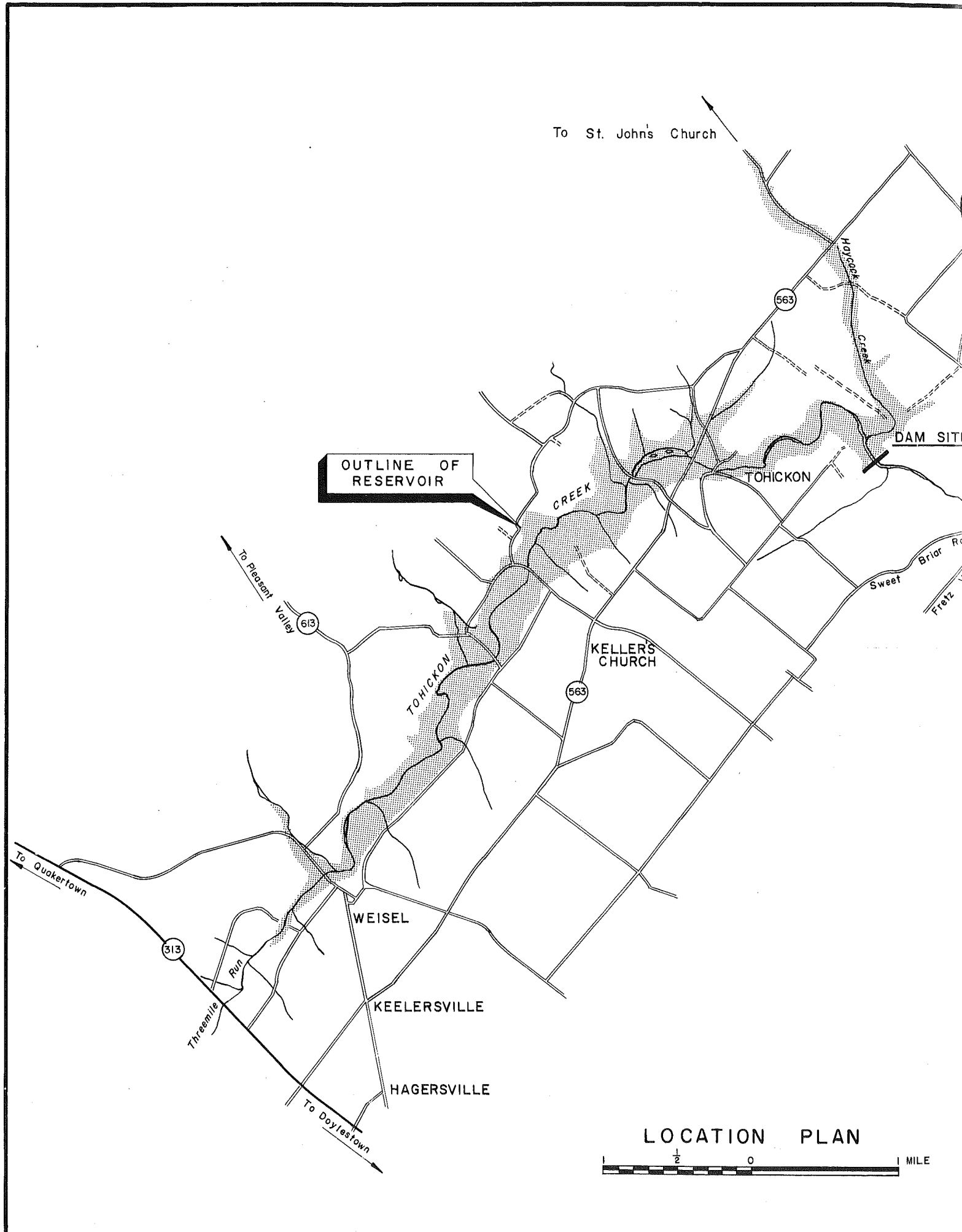
LIST OF ILLUSTRATIONS,
T A B L E S , A N D P H O T O G R A P H S (continued)

<u>Number</u>	<u>Title</u>	<u>Page</u>
20	Vortex at Inside Corner with 100% Flowrate - Original Design	38
21	Second Jump at 100% Flowrate - Original Design	40
22	Second Jump at 20% Flowrate - Original Design	40
23	First Jump at 100% Flowrate - Final Design	42
24	Elimination of Vortex - Final Design at 100% Flowrate	42
25	First Jump at 20% Flowrate - Final Design	43
26	Elimination of Vortex - Final Design at 100% Flowrate	43
27	Second Jump at 100% Flowrate - Normal Tailwater - Final	44
28	Original versus Final Design Comparison Contour - 100% Flowrate	45
29	Weir Cross Section Comparison - 20% Flowrate	47
30	Weir Cross Section Comparison - 60% Flowrate	48
31	Weir Cross Section Comparison - 100% Flowrate	49
32	Original Forebay With Smooth Flow at 100% Flowrate	50
33	Forebay Modification No. I	52
34	Forebay Modification No. II at 100% Flowrate	53
35	Forebay Modification No. III (final) at 20% Flowrate	54
36	Forebay Modification No. III (final) at 100% Flowrate	55
37	Flowrate versus Forebay Water Surface Elevation Comparisons	57
38	Surface Profile Along Left Concrete Retaining Wall - Final Design at 100% Flowrate	58
39	Prototype Velocities at Critical Locations	59
40	Mesh Orientation	61
41	Effect of Mesh Orientation on First Hydraulic Jump	62

I. I N T R O D U C T I O N

A. Purpose of Study

The Commonwealth of Pennsylvania has committed over seventy million dollars for "Project 70" to increase the number of recreational facilities for its people. As part of the project, a new state park will be formed in Bucks County which will be known as Nockamixon State Park. Originally a two-stage development was planned, as envisioned by the Delaware River Basin Report; however, because of the small amount of additional land required for ultimate stage development and also the limited additional captial costs for the dam required for such development, the Department of Forests and Waters decided for ultimate development of the Tohickon Site. The central feature of the 5000 acre park, which is to be constructed by 1970, will be a lake seven miles long created by a 100 foot high and 1200 foot long dam. The dam which is to be of earth and rock fill construction will be built across the Tohickon Creek just downstream of its confluence with Haycock Creek. The dam site is located near the town of Ottsville, 10 miles east of Quakertown, and about 30 miles north of Philadelphia, Pennsylvania, (Figure 1). The extent of the drainage area and outline of the reservoir to be impounded by the dam can be seen in Figure 2. The area of the reservoir will be 1460 acres and the gross storage will be approximately 41,000 acre feet, or 13.4 billion gallons.



To St. John's Church

OUTLINE OF RESERVOIR

CREEK

TOHICKON

DAM SITE

To Present Valley

To Quakertown

KELLER'S CHURCH

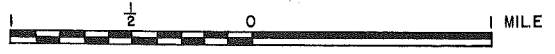
WEISEL

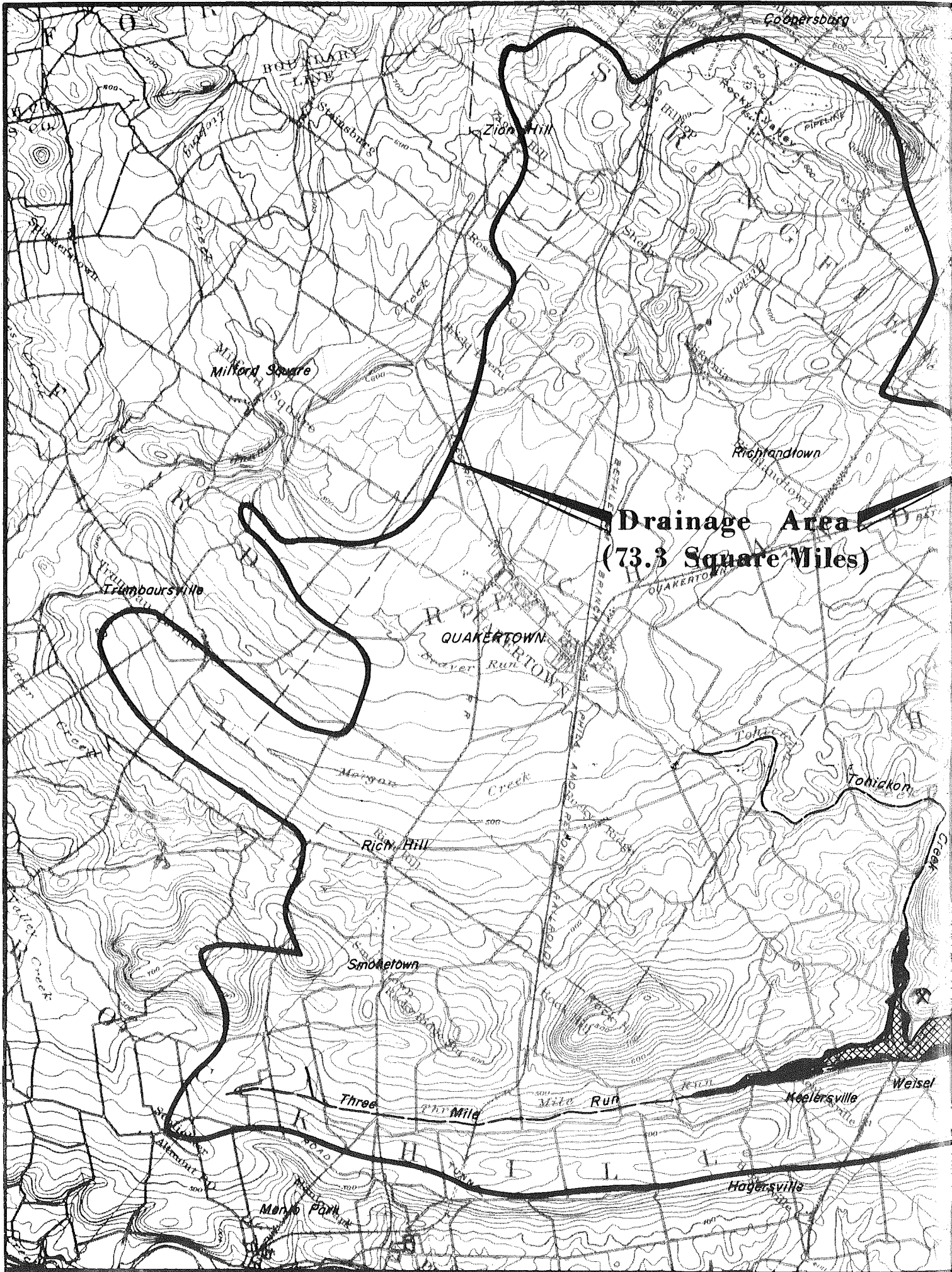
KEELERSVILLE

HAGERSVILLE

To Doylestown

LOCATION PLAN





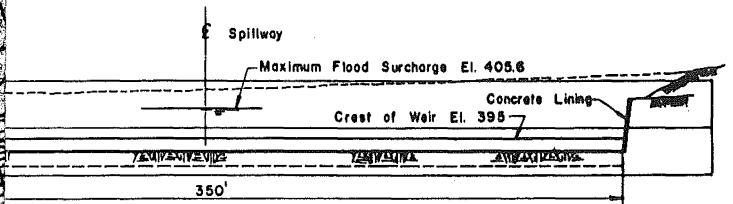
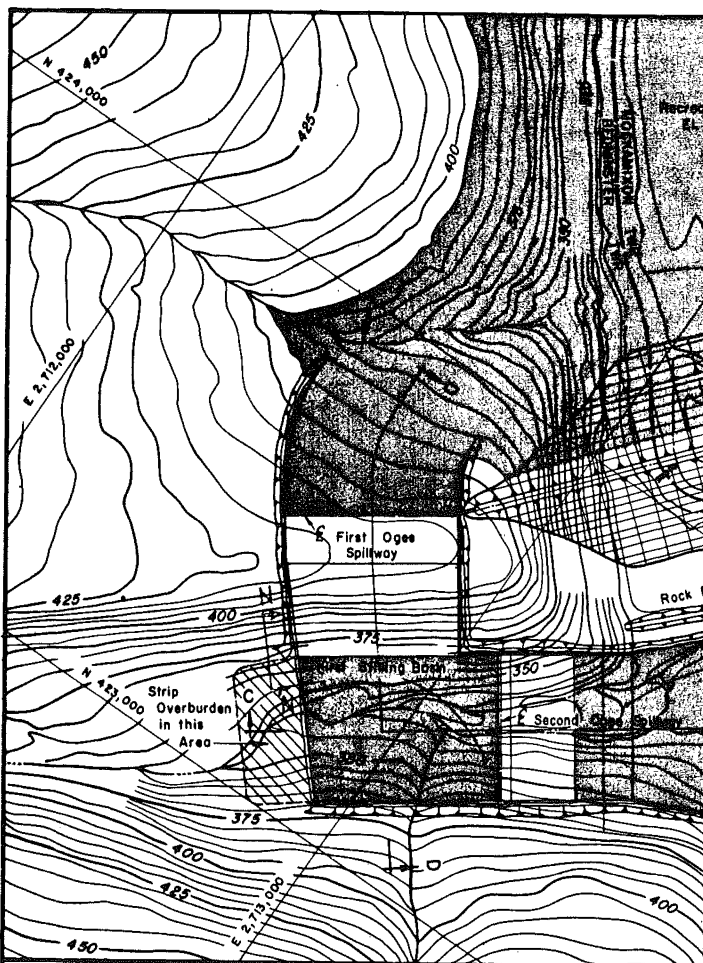
Drainage Area
(73.3 Square Miles)

The spillway design, to handle the Standard Project Flood expected in the area, was based on hydraulic requirements and construction economy. It was desired to make the spillway as wide as possible to protect the park beaches and limit the surcharge during large floods. The topography of the area necessitated the unusual geometric design. As seen in Figure 3, a natural draw occurs in the terrain making an ideal location for the return channel to the river downstream of the dam. However, in order to take advantage of this natural site the spillway flow will have to make a ninety degree turn after it passes over the control weir located on the west side hill. The spillway if located and constructed as shown in Figure 3 would provide enough good quality rock to construct the dam to the required elevation. It was therefore decided to design the spillway with the ninety-degree turn. Additional sectional views of the spillway design are shown in Figure 4.

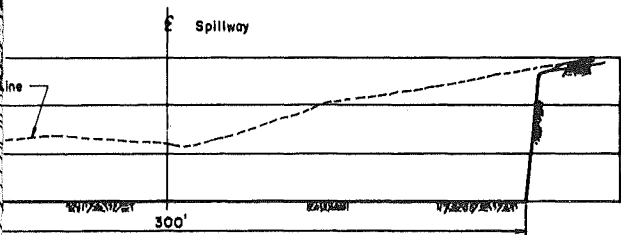
Because of insufficient theoretical knowledge of supercritical flows in open channels, exact computations cannot be made of the surface elevations and velocities for flow around a sharp ninety-degree turn. The location of areas of flow separation and vortices accompanying such flows is also impossible to determine. The General State Authority therefore requested that a hydraulic model be made to determine the exact performance characteristics of the ninety-degree spillway, as designed by the Consulting Engineers.

In particular the model study was desired in order to:

1. Check the overall hydraulic flow patterns in the spillway resulting from the unusual design.

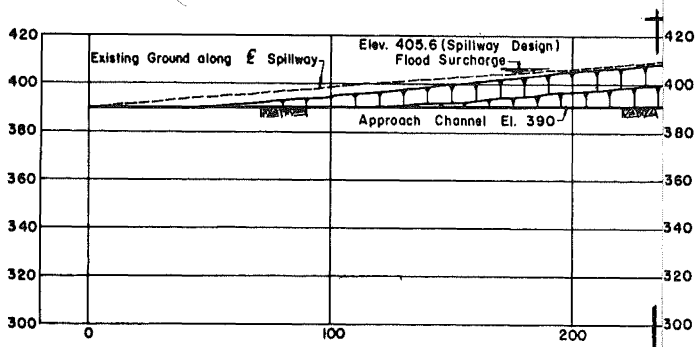
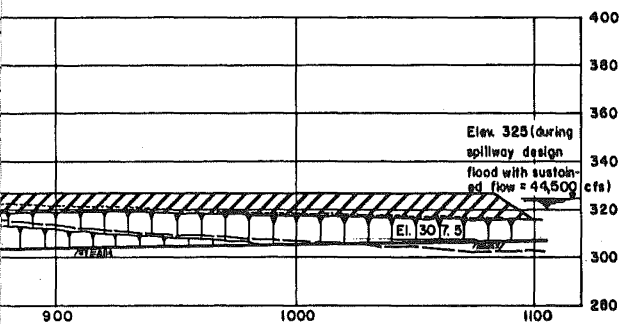
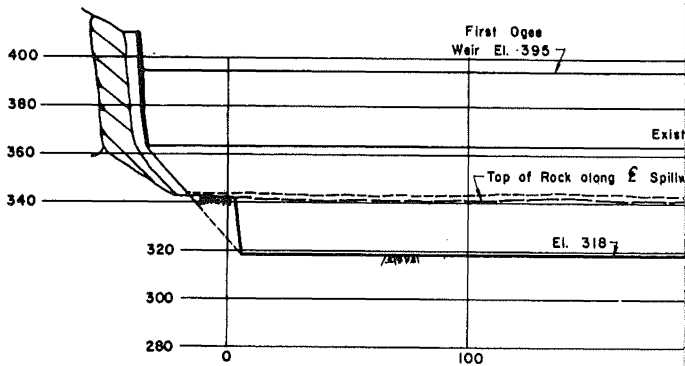


SECTION A-A



SECTION B-B

PLAN



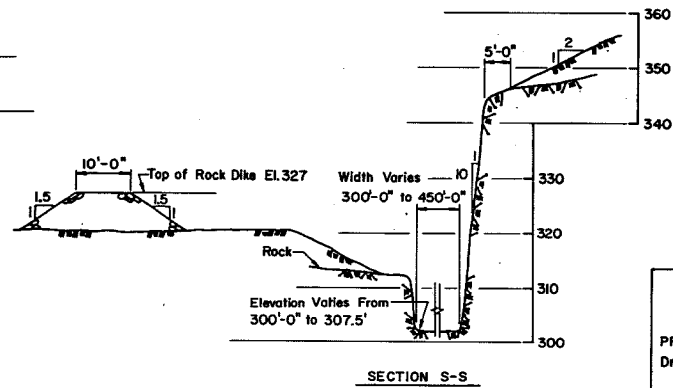
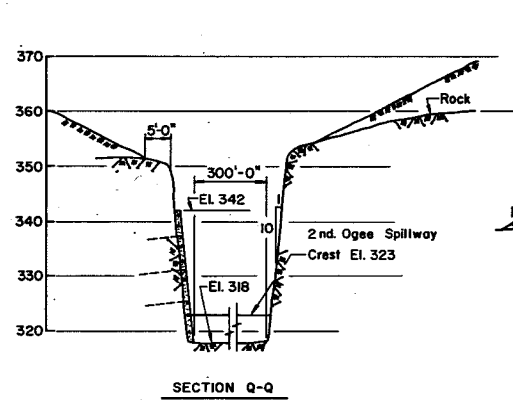
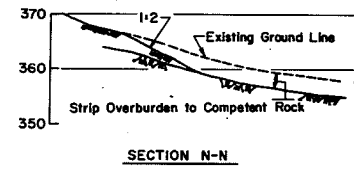
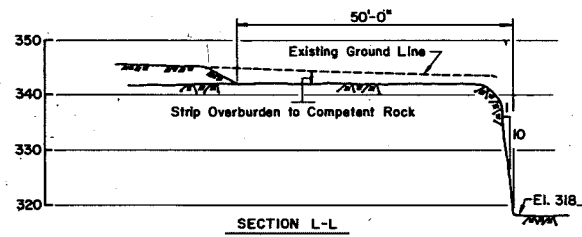
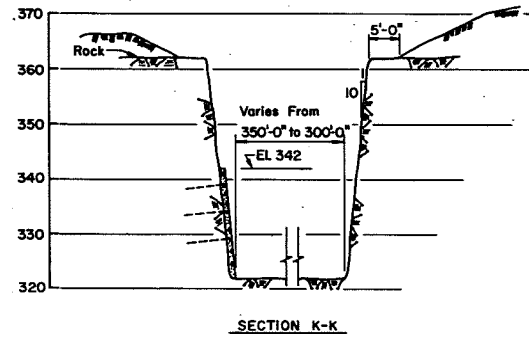
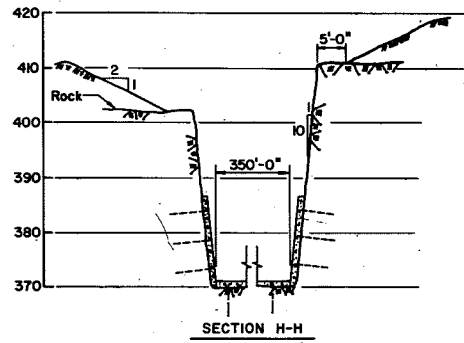
Project No. G.S.A. 194-12
Dam

Nockamixon State Park
Bucks County, Pennsylvania

PROPOSED SPILLWAY DESIGN

Drawing Courtesy of
Pickering, Corts and Summerson, Inc.
Langhorne, Pennsylvania
Lehigh University, Fritz Engin. Lab.
Fig. No. 3

SCALE: 1" = 80'



Project No. G.S.A. 194-12
 Dam
 Nockamixon State Park
 PROPOSED SPILLWAY SECTIONS
 Drawing Courtesy of
 Justin E Courtney
 Philadelphia, Pennsylvania
 Lehigh University, Fritz Engin. Lab.
 Fig. No. 4

2. Provide the necessary design information for concrete linings, wall heights, and the proposed protective dike.

3. Insure the overall safety of the dam under the worst projected flood conditions.

B. Model Scale

Since the forebay entrance area ahead of the first ogee weir affects flow in the spillway, it must be modeled carefully. Enough of the entrance area must be modeled so that the model flow patterns simulate as closely as possible those expected to occur in the prototype.

Modeling the tailwater area is not as critical. As long as the correct tailwater elevation is maintained the model can deviate somewhat from geometric similarity in this case.

Exact geometric similarity is important throughout the entire spillway flow passages. In this regard the slopes of all walls, all warped areas and all weir curvatures must be carefully scaled.

Laboratory space was the governing factor in determining the smallest possible model scale. After a careful analysis of all possible laboratory locations and model scales, a model of 60 to 1 was chosen. This scale is well within the 100 to 1 range when surface tension forces begin to influence the results.

Most important and unfortunately most difficult is the art of modeling the exact surface roughness so that the frictional resistances

in the model will be dynamically similar to those in the prototype. Since the prototype surface roughness after rock blasting is extremely non-uniform and indeterminate, exact modeling is impossible. Details of the model roughness calculations, methods used and tests made and planned are given in the Theoretical Analysis Section of this report.

C. General Test Program

The original spillway design was tested with both a smooth and artificially rough channel surface and after the latter test it became apparent that a modification study was also necessary. The spillway modifications were made in two steps and the second step became the final design configuration.

The forebay was also redesigned and after a series of four arrangements, modification No. III became the final configuration.

Some minor tests with the artificial roughness were also performed.

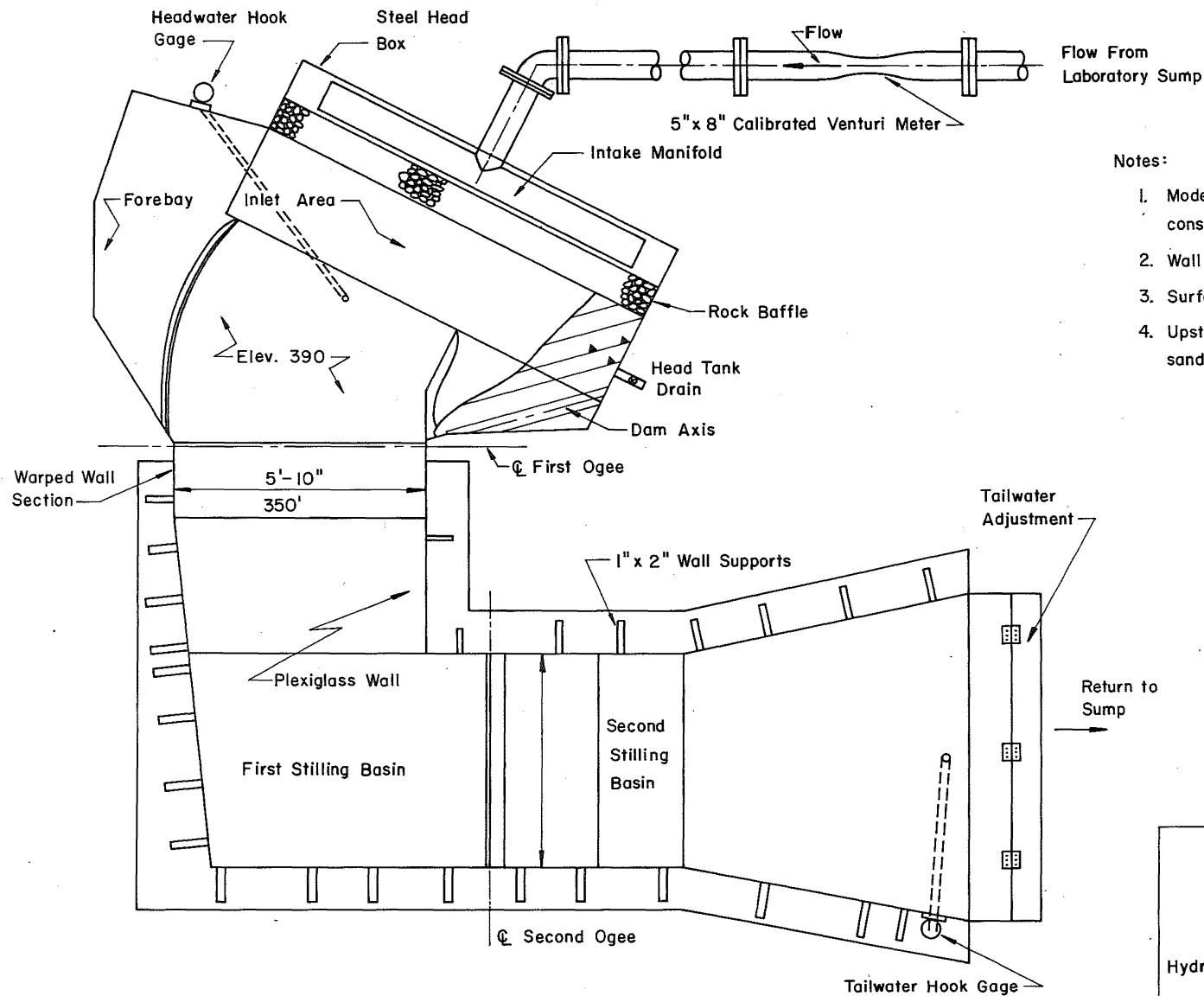
II. MODEL TEST FACILITY

A. Original Model Design

The plan and elevation views of the model as originally constructed in the Hydraulics Division Laboratory are shown in Figures 5 and 6. (See Frontispiece also).

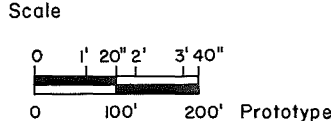
The head box was constructed of steel plate, and a heavy expanded metal lath was used to support the rocks in the rock baffle. Wood was used to construct the remainder of the model. Floors and walls were cut from marine plywood sheets to eliminate warping. Cross braced Kiln-dried two by fours and two by sixes were used for all beams and for the leg columns to insure against misalignment. A stiff cement grout was used to mold the forebay ground contours between templates cut from masonite sheets and the corner of the dam was modeled from 1/16 inch galvanized sheet steel.

Since change is the rule rather than the exception in hydraulic models, the model was designed for ease in adjustment and modification. It was built in sections which were either hinged or bolted together to allow for fast leveling to exact floor elevations and to facilitate any necessary modifications in design. (See Figure 7) The 4 to 1 sloping section was hinged at the first ogee to readily make slope changes and all two by four legs were fitted with leveling screws so that floor

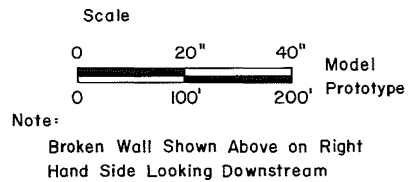
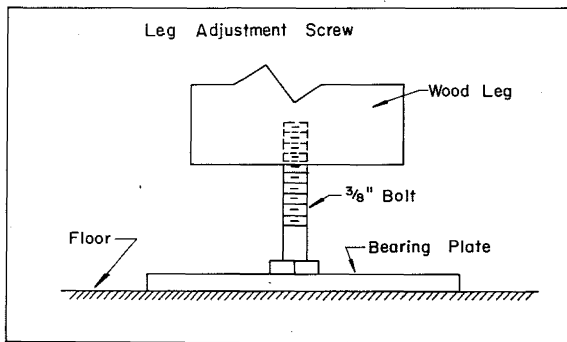
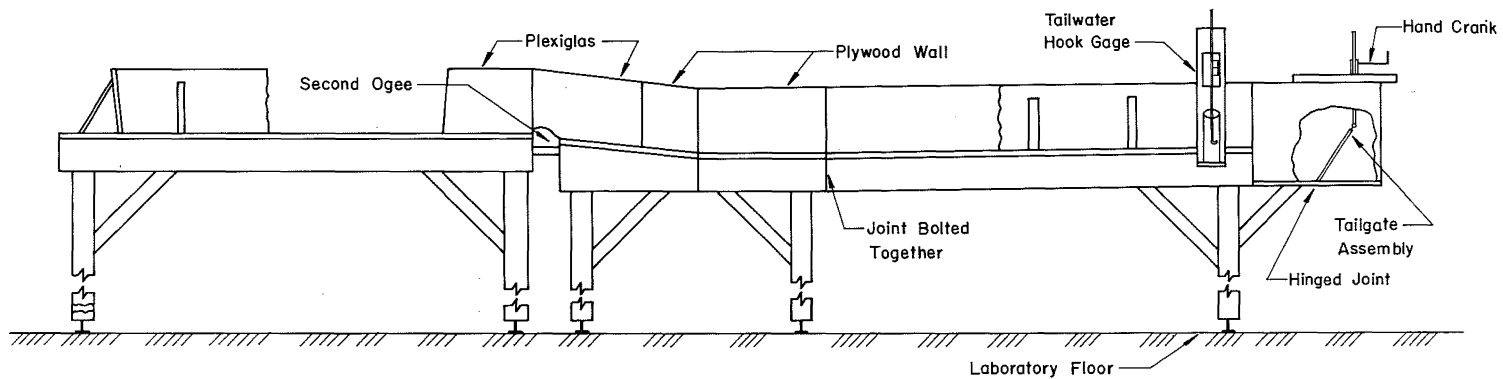
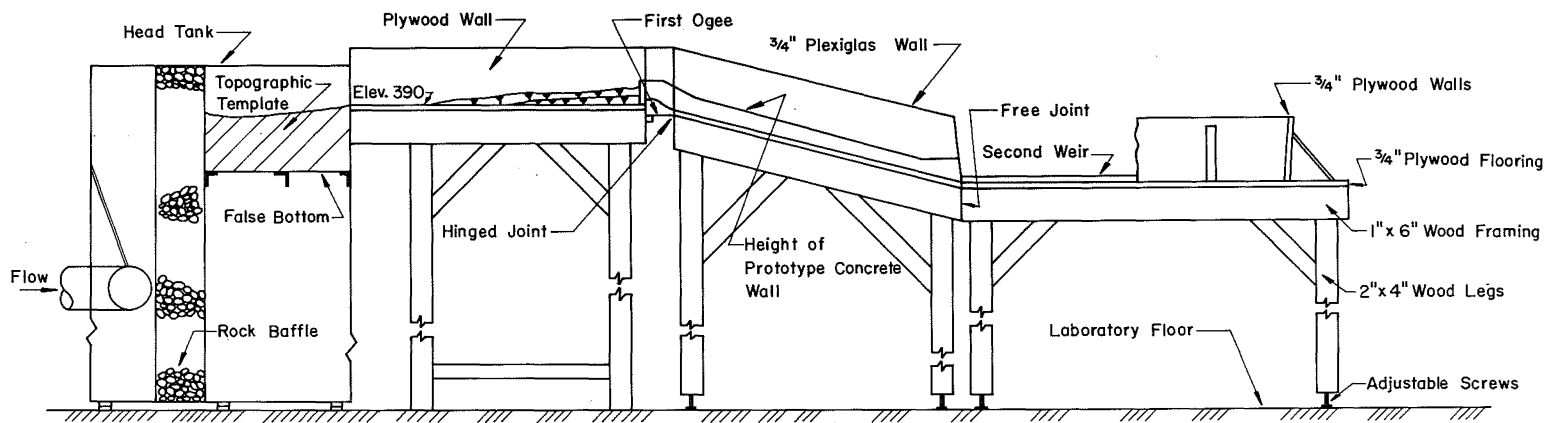


Notes:

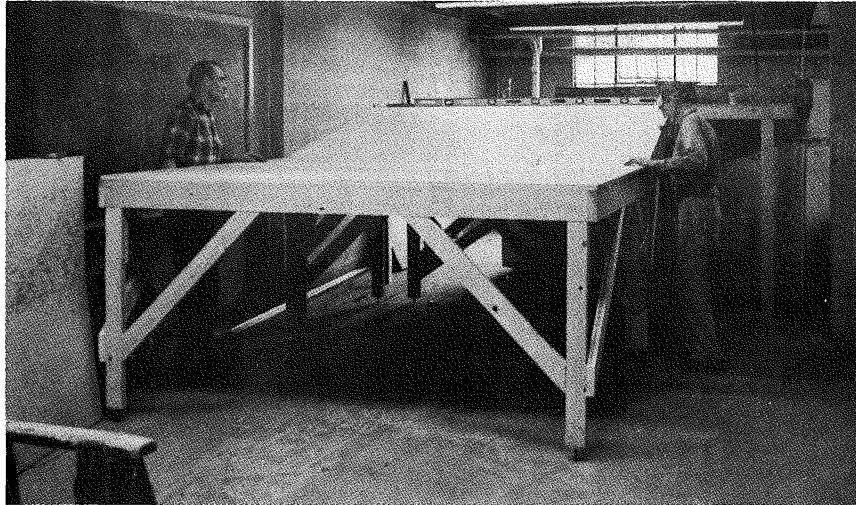
1. Model downstream of First Ogee constructed of $\frac{3}{4}$ " marine plywood
2. Wall slopes 1 horizontal to 10 vertical
3. Surface roughness not shown
4. Upstream topography Constructed of sand-cement grout



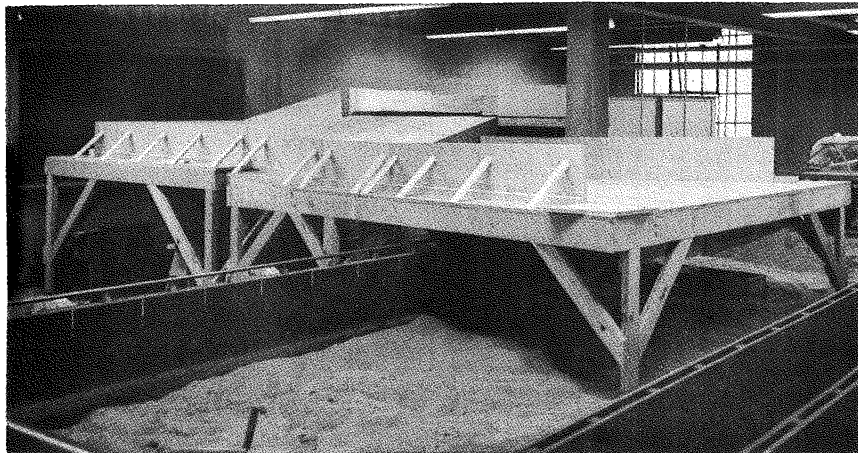
Project I050-326
 Nockamixon Spillway Model
 ORIGINAL MODEL PLAN
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University
 Fig. No. 5



Project IO50-326
 Nockamixon Spillway Model
 ORIGINAL MODEL SECTIONS
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University
 Fig. No. 6



(a) Table for first stilling basin being moved into position.



(b) Second table in place with some walls attached.

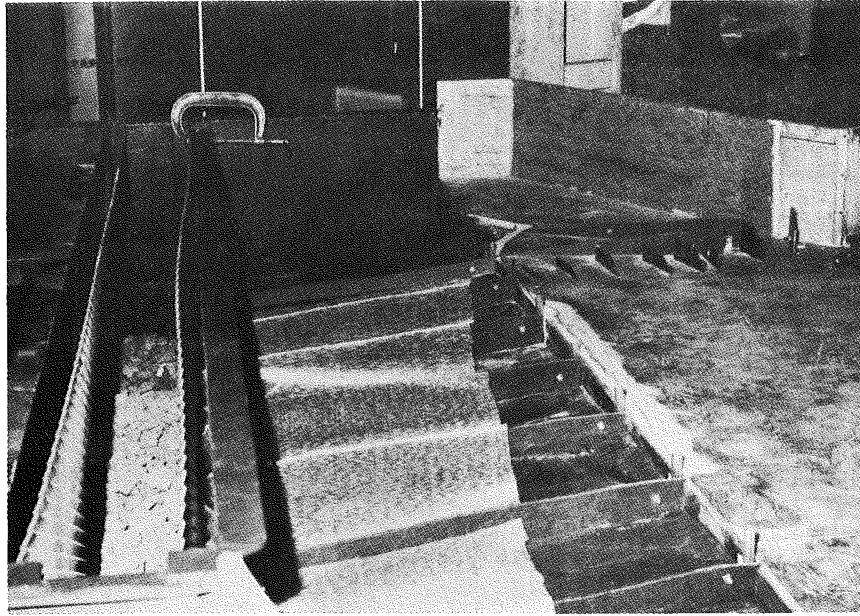
Fig. No. 7 Model Construction

elevations could be set with a Dumpy level and rod. Elevations could thus be set to ± 0.15 feet on the prototype scale.

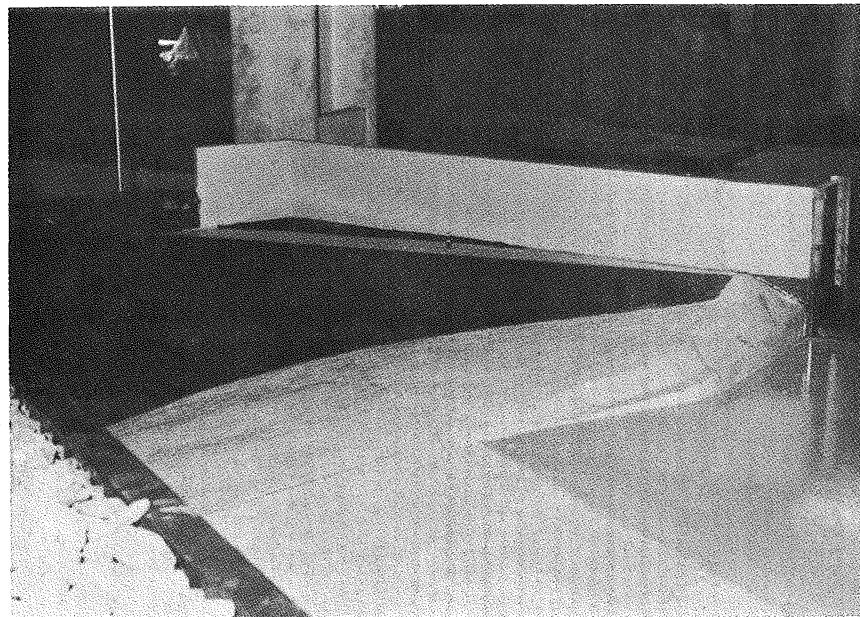
The laboratory's main pumping system was used to provide water to the model. Water was pumped from the laboratory sump and returned via the second floor drain for recycling. The flow was measured with a calibrated venturi meter and controlled by a gate valve upstream from the head box. A six inch diameter distribution manifold with jets facing upstream resulted in a uniform flow distribution into the head box. The six inch wide rock baffle with 1/2 to 3/4 inch crushed and washed stone insured uniform flow into the model.

Both the first and second ogee weirs were precisely cut from hardwood by the Bethlehem Model Shop, Bethlehem, Pennsylvania. Reverse templates were used to insure the exactness of the weir profiles over their entire length.

Figure 8 shows some details of the method of forebay construction. A false floor was constructed in the head box up to the rock baffle. On it and the floor extending from the steel head box, templates cut from 1/4 inch masonite sheet were attached to aid in contouring the ground surface. The template profiles were cut to match the existing topography in the area and a light weight aggregate was poured over the entire forebay area to be contoured to within an inch of the template surface to lighten the load on the wooden flooring. Finally, a thick sand-cement grout was hand placed and contoured to form an exact model of the topography in the forebay area. Surface elevations were checked to within ± 0.5 feet on the prototype scale.



(a) View before pouring grout between templates



(b) After modeling surface contours with grout - corner of dam in place.

Fig. No. 8 Forebay Construction

Wall sections at the inside corner were made from 3/4 inch plexiglass so that visual observations of the turbulence and flow patterns in this critical area could be made.

The tailgate was hinged to the model and held in place by two 3/8 inch diameter, 16 threads per inch, bolts fitted with hand cranks. This arrangement permitted fast and accurate adjustment of the tailwater to values above and below the required levels.

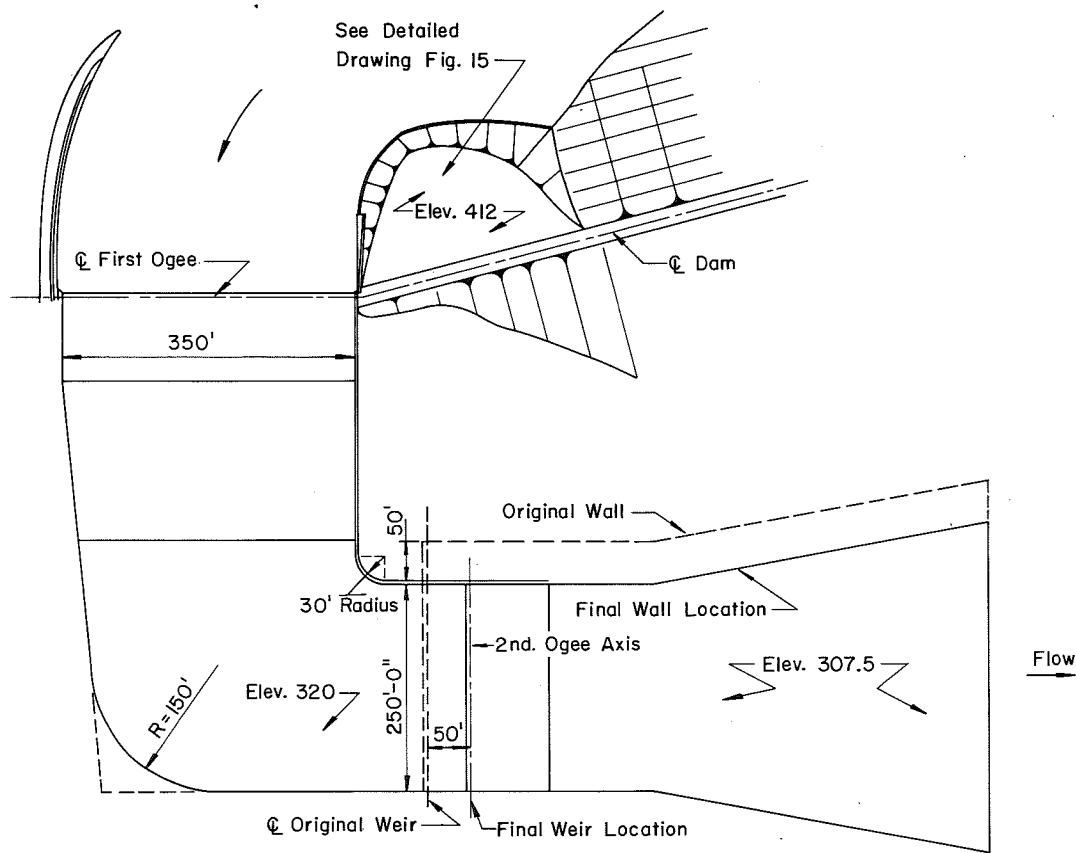
An expanded metal lath was selected to simulate the floor and wall roughness for reasons of economy and ease of construction.

B. Modifications

1. Spillway

The modifications to the original spillway design were made in two steps. Step one, called Part A, involved moving the left side concrete retaining wall 50 feet (in the direction of the stream's centerline) thereby reducing the second weir length to 250 feet. The inside and outside radii were also added at this time. The location and design of the second weir ogee remained unchanged. All floor elevations did not change from original design. The modified spillway (Part A modifications as noted) is shown in Figure 9.

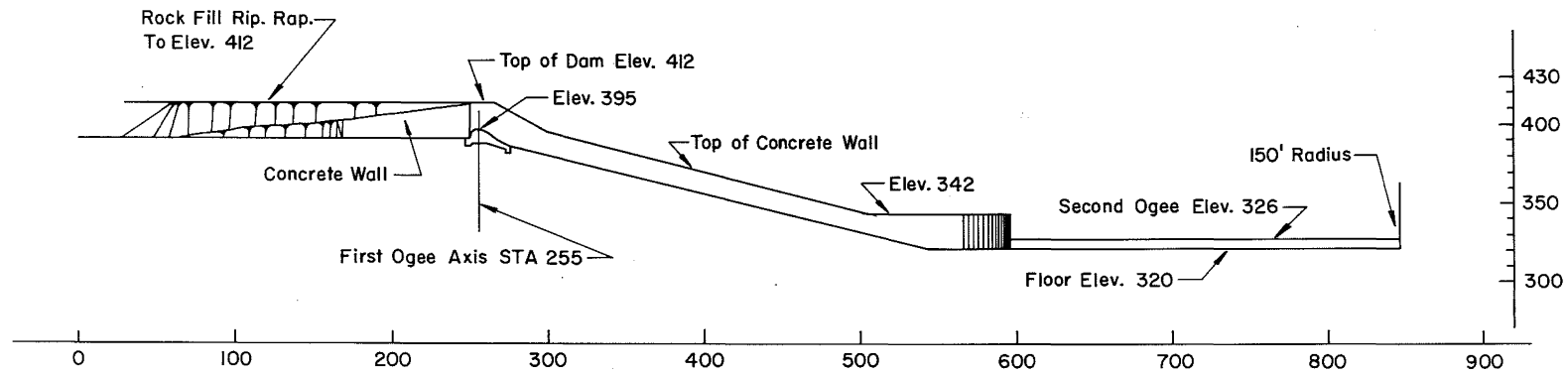
Part B resulted in the final design. In this second part of the modification program the first stilling basin floor elevation was raised two feet to Elevation 320 feet, and the second ogee weir was moved downstream and completely changed in design. The modified spillway is shown in Figures 9 and 10 with the original outline superimposed.



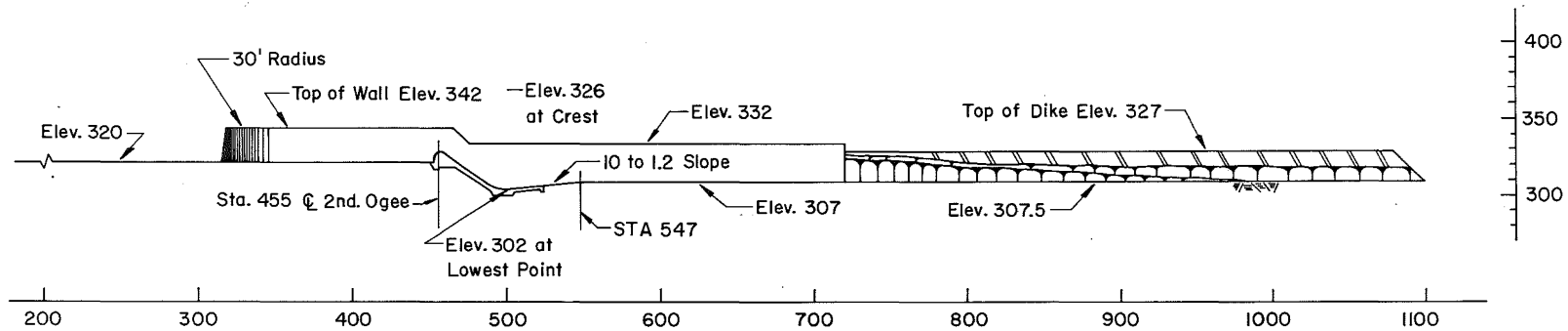
Note:

1. Part A of modifications included only 30' and 150' radii shown and decreased width of second ogee as shown. Elevation view remained as originally shown.
2. Final design of spillway shown with final forebay design.

Project I050-326
 Nockamixon Spillway Model
 MODIFIED SPILLWAY PLAN
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University
 Fig. No. 9



ELEVATION VIEW FIRST OGEE TO FIRST STILLING BASIN

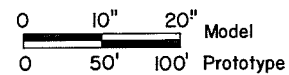


ELEVATION VIEW FIRST STILLING BASIN TO TAILRACE

Note:

See Justin and Courtney dwg. no. 647-A for details of second ogee shape.

Scale

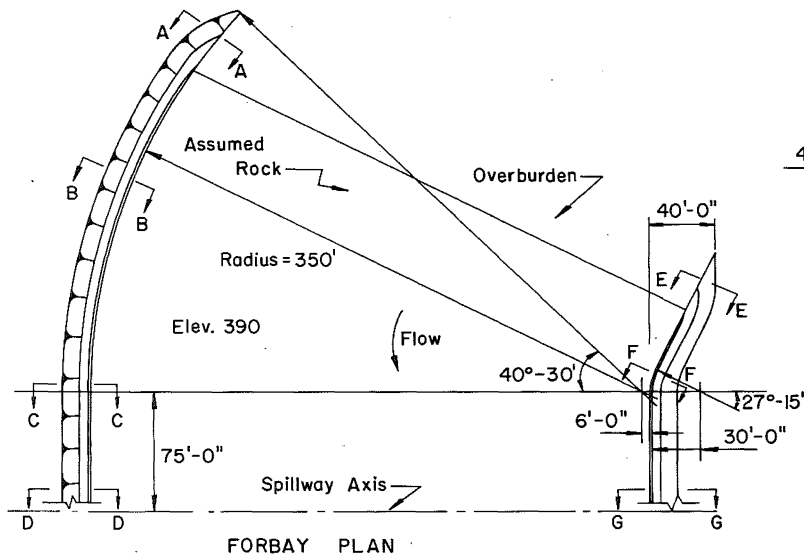


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 Nockamixon Spillway Model
 MODIFIED SPILLWAY SECTION
 Fritz Engineering Laboratory
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 Lehigh University
 Fig. No. 10

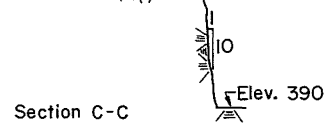
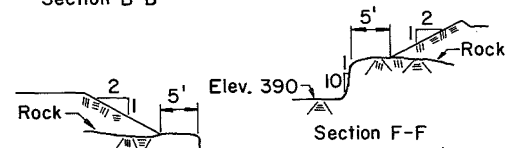
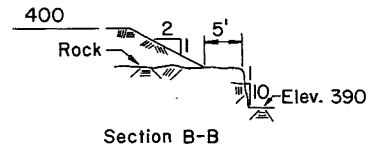
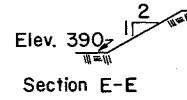
Note also that the floor elevation profile was also completely changed downstream of the second weir for the modified design.

2. Forebay

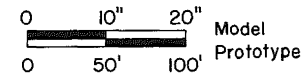
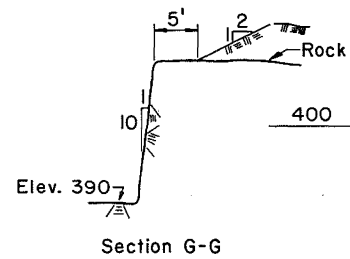
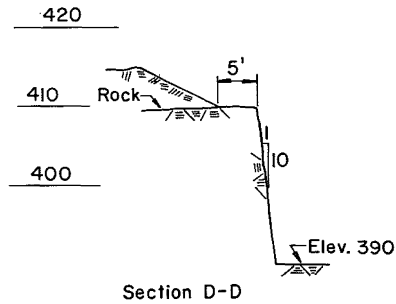
Figures 11 and 12 give complete details of the original forebay area design. Three modifications of the original design were made and studied. After the original tests, Forebay Modification No. I shown in Figure 13 was suggested by the Consulting Engineers (Justin and Courtney) and appropriate model changes made to test this design. Of primary concern was the poor hydraulic entrance conditions that resulted in inefficient flow on the left side of the first weir. The large fill area and warped slope seen in Figure 13 was made to streamline the flow as it approached the first weir. Modification No. II, shown in Figure 14, was made by Lehigh University in search of further improvement. However, this design proved impractical due to the length of the rock fill warped section. Figure 15 gives details of Modification No. III which was incorporated in the final design.



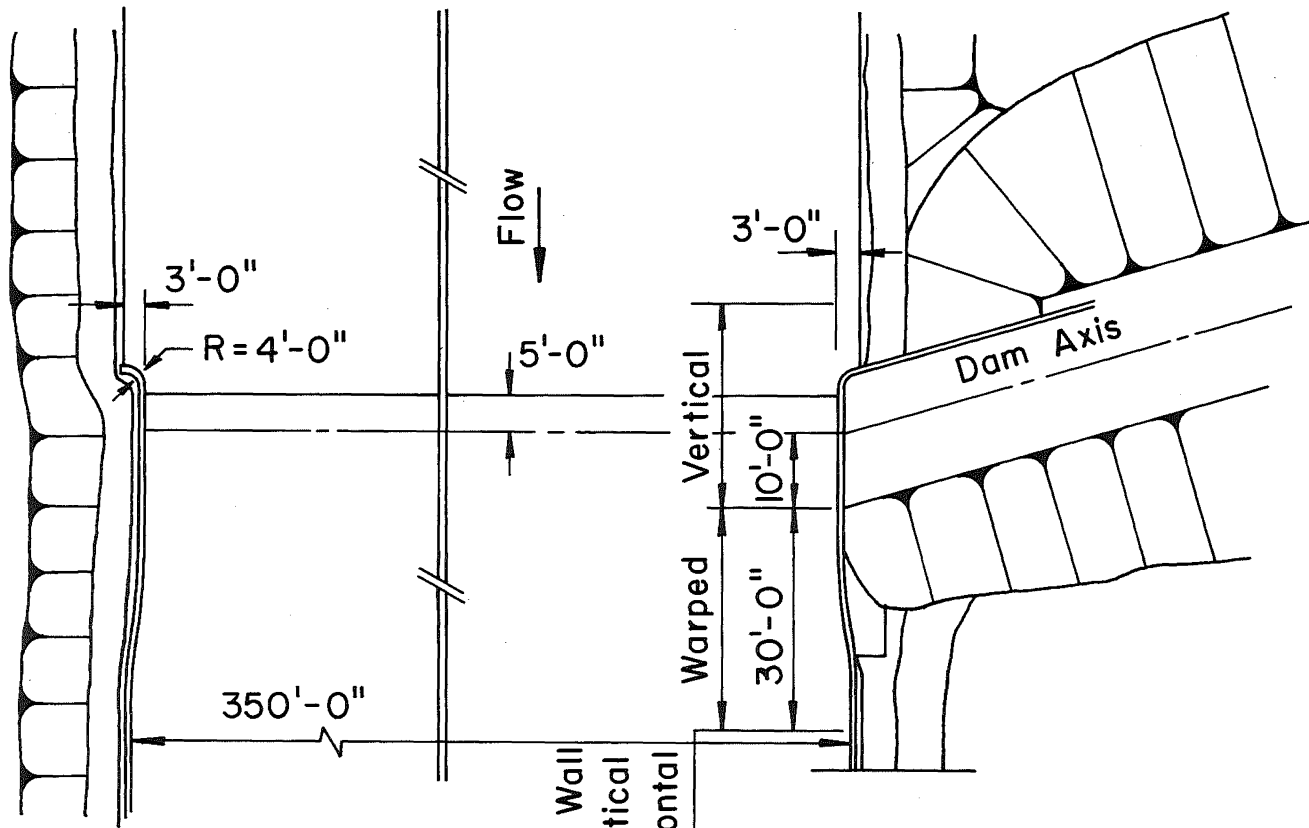
Elev. 400



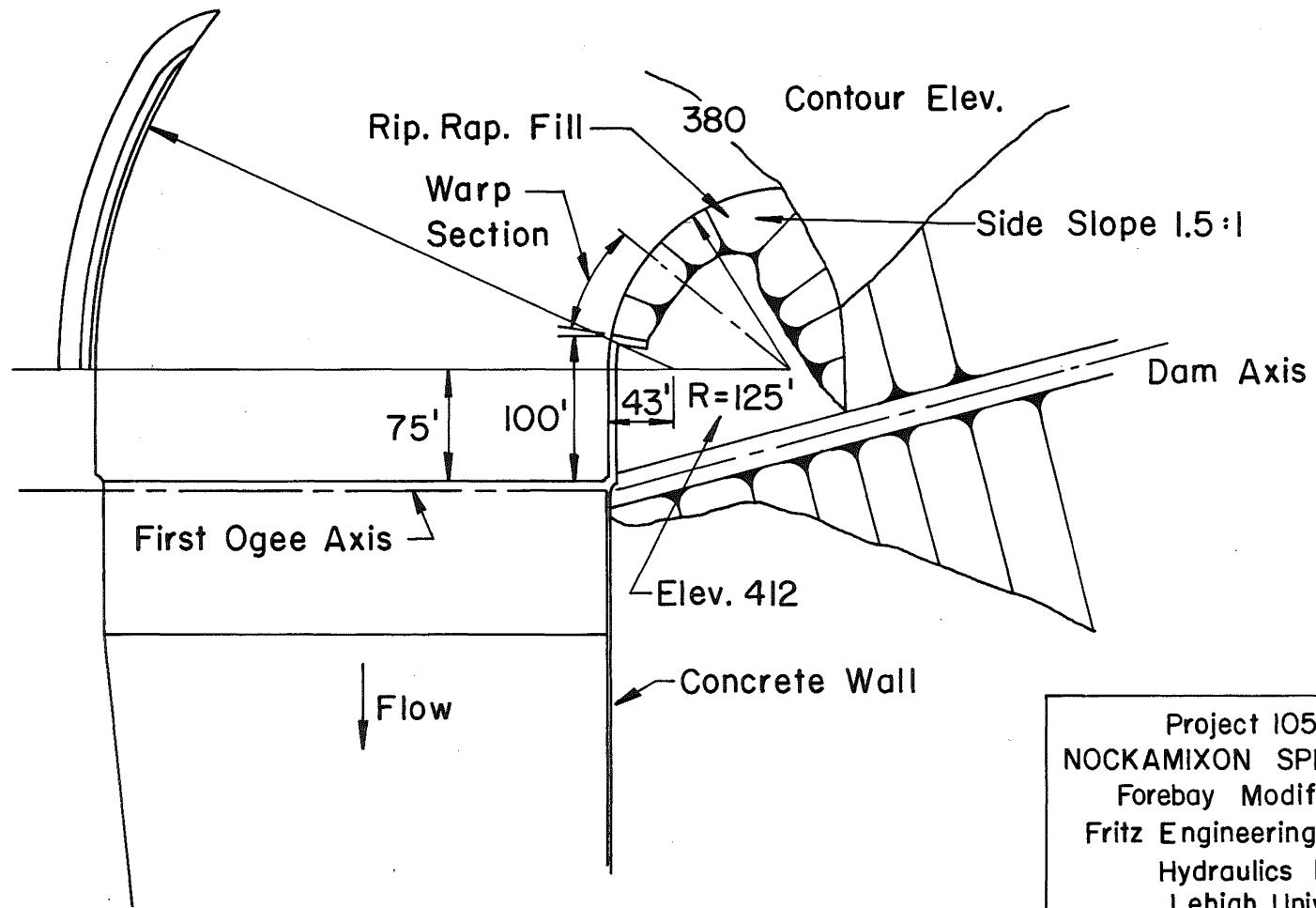
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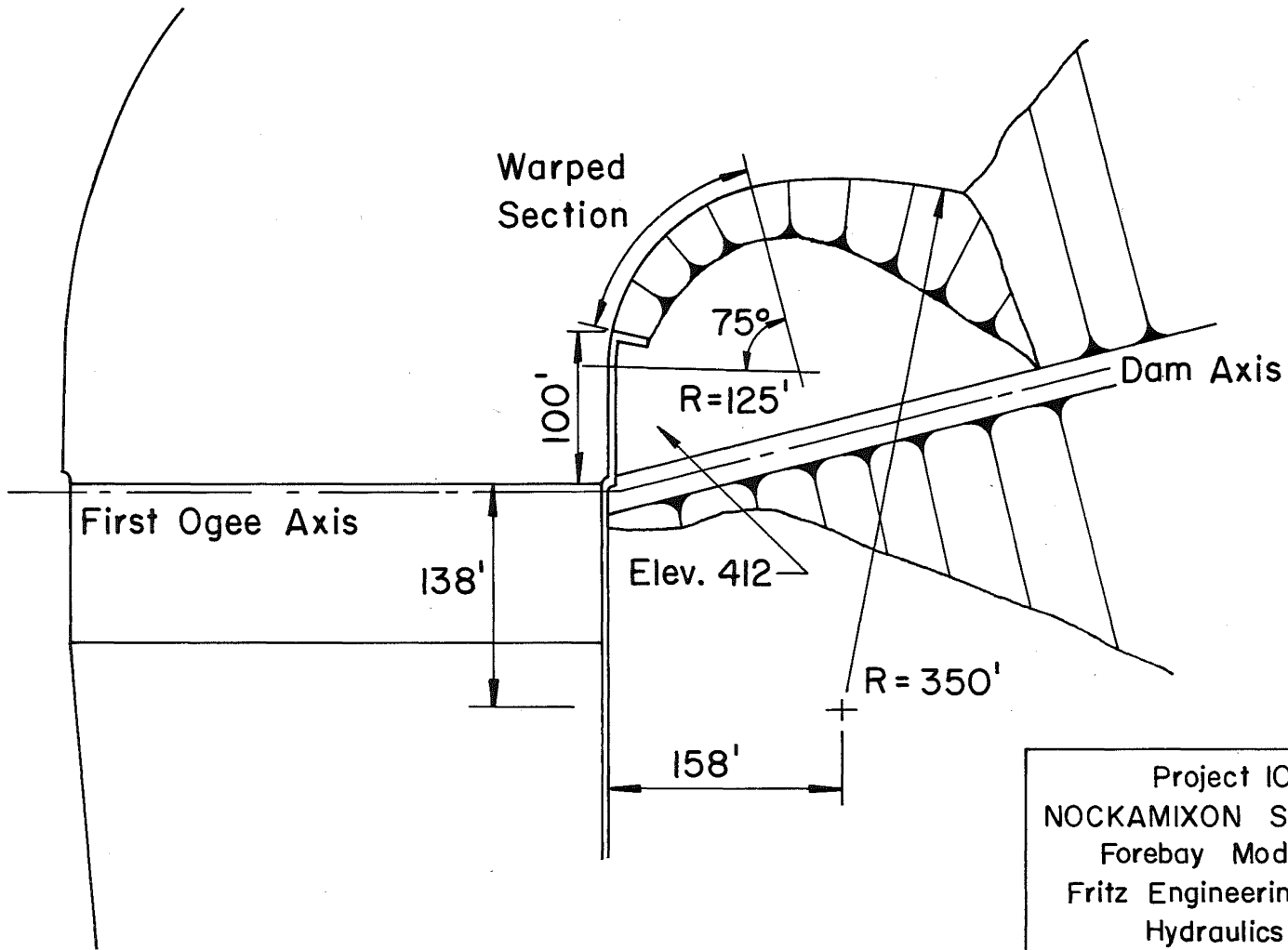
Project 1050-326
Nockamixon Spillway Model
ORIGINAL FORBAY PLAN AND SECTIONS
Fritz Engineering Laboratory
Hydraulics Division, Civil Engineering Dept.
Lehigh University
Fig. No. 11



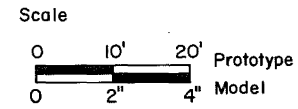
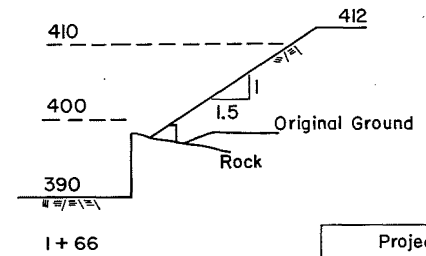
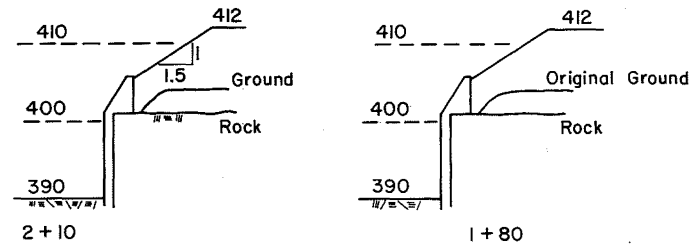
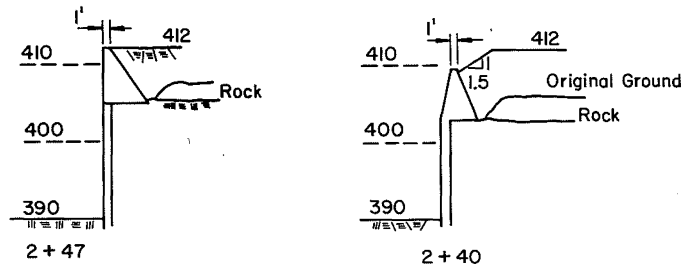
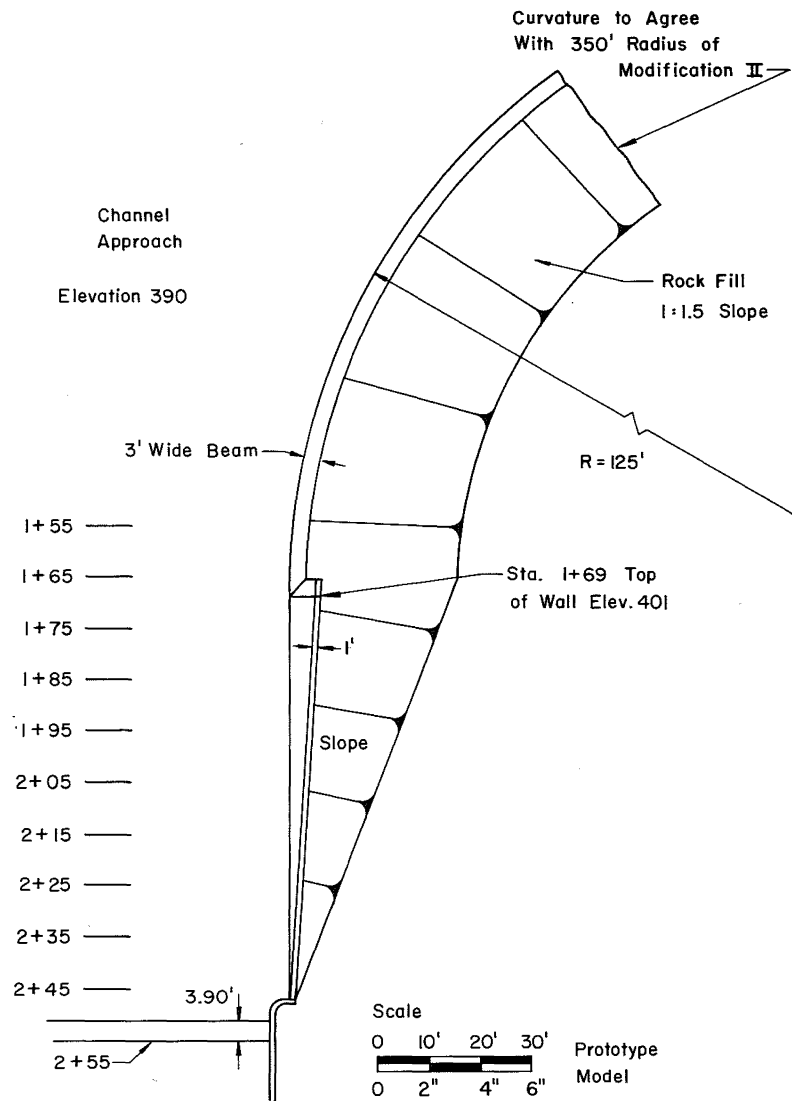
Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 Original Forebay and
 Weir Plan
 Fritz Engineering Laboratory
 Hydraulics Division
 Lehigh University
 Fig. No. 12



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 NOCKAMIXON SPILLWAY MODEL
 Forebay Modification-I
 Fritz Engineering Laboratory
 Hydraulics Division
 Lehigh University
 Fig. No. 13



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 NOCKAMIXON SPILLWAY MODEL
 Forebay Modification - II
 Fritz Engineering Laboratory
 Hydraulics Division
 Lehigh University
 Fig. No. 14



Project 1050-326
Nockamixon Spillway Model
FOREBAY MODIFICATION
NO. III - FINAL
Fritz Engineering Laboratory
Hydraulics Division
Lehigh University
Fig. No. 15

III. INSTRUMENTATION

A minimum amount of instrumentation was needed to obtain all the experimental data. Most important was the determination of flow-rate so that the correct floods could be simulated in the model. In this regard the eight inch by five inch venturi meter in the supply line was recalibrated prior to the test program. The results of the calibration using the volumetric method are shown in Figure 16. The calibration was checked during the testing program and no deviation noted. Extreme care was used to bleed the manometer lines of air before each test.

Two hook gages in pot-type stilling wells were used to determine and set the head water and tailwater surface elevations. (See Figure 5). The zero reading was set on each hook gage using a Dumpy level and rod.

Water depth measurements were made with an ordinary point gage. In some cases high and low water depth readings were taken and an average value calculated. A coordinate system had to be established to locate each depth measurement for later plotting purposes. The prototype stationing system used on Figure 3 was used since the results could be easily referenced back to the prototype for evaluation. The spillway profile stations along Section C-C of Figure 3 were designated

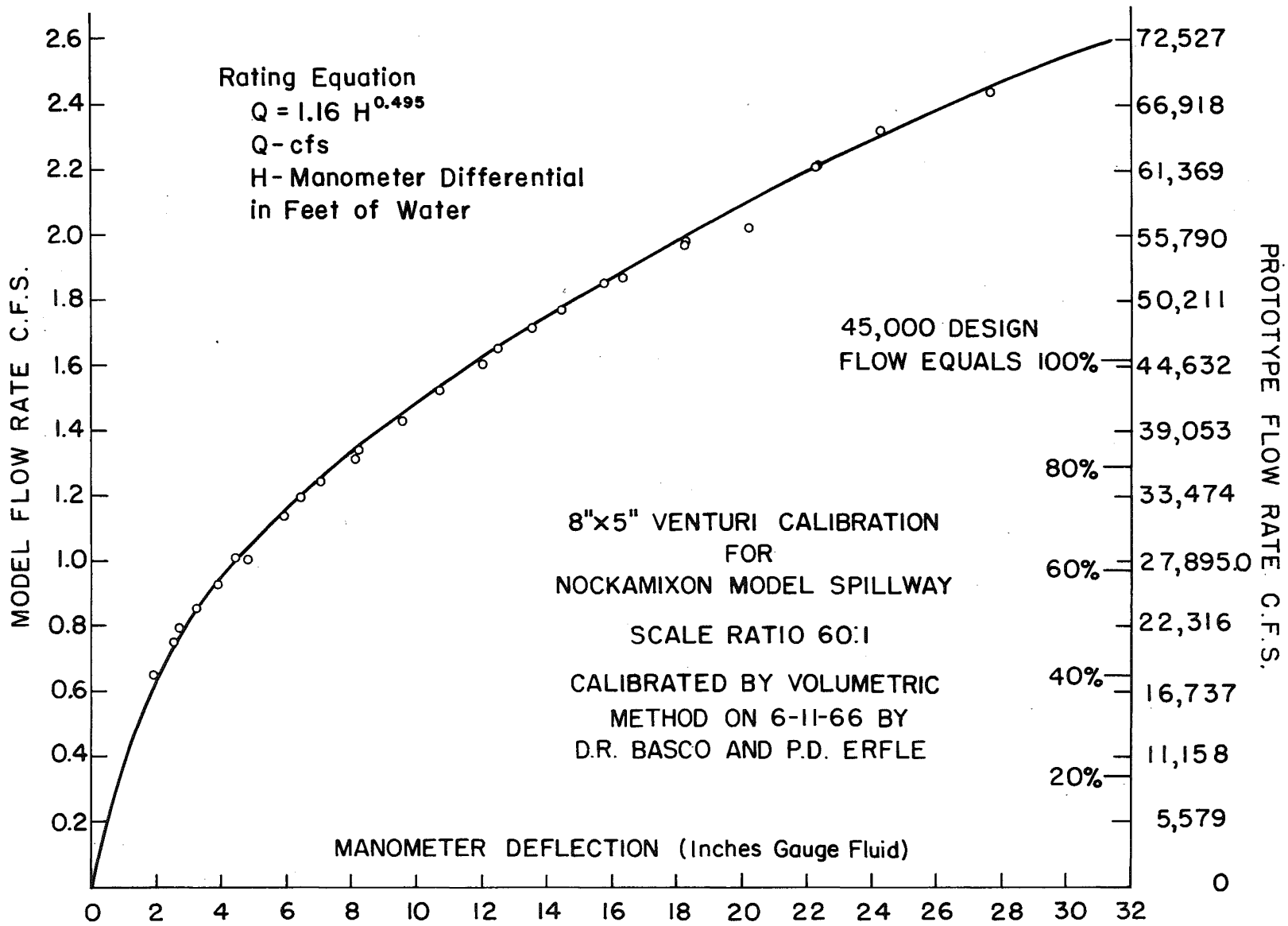


Fig. No. 16

the "Red Scale". Along Section D-D the term "Black Scale" was used. The point gage bar was also stationed to prototype scale and called the "Blue Scale". These designations were all used on the test result plots and are referred to in the section on test results.

Velocity measurements were made with a Leupold & Stevens midget current meter. The calibration curve of this meter was checked using the laboratory open-channel flume.

IV. THEORETICAL ANALYSIS

A. Model Laws

The model was tested according to the general practice for open channel, free surface flows. Both the Reynolds Number and Froude Number appear in a non-dimensionalized Navier-Stokes equation, indicating that both viscous and gravity forces govern the flow. Standard practice has been to design the model according to the predominant Froude Law, while qualitatively noting the viscous force effects on the results. Experience has shown that for models built for scales less than 100 to 1 the surface tension effects at the boundary are negligible.

Using the Froude Law therefore, the following relationship were used in all calculations:

$$\text{Length ratio, } L_r = \frac{L_p}{L_m} = 60 \quad (1)$$

$$\text{Velocity ratio, } V_t = \frac{V_p}{V_m} \quad (2)$$

$$= \sqrt{L_r} g_r = 7.745$$

$$\text{Discharge ratio, } Q_r = \frac{Q_p}{Q_m} \quad (3)$$

$$= L_r^{5/2} \sqrt{g_r} = 27,850$$

where: L = length
 V = velocity
 Q = volumetric flowrate
 g = gravitational constant, $g_r = 1.0$ on earth
 p = subscript referring to prototype
 r = subscript referring to ratio
 m = subscript referring to model

Pressure, force, power, etc. relationships were not involved.

Using conventional methods the water surface profiles for the spillway can be predicted only in the straight sections of the channel. Chow⁽⁴⁾ gives methods for predicting surface elevations and losses around bends in smooth curved channels. However, there is no accurate information to the writer's knowledge about open channel flow around sharp, ninety-degree turns.

B. Channel Roughness

According to the best estimates of the Design Engineers, (Pickering, Cortis and Summerson, Inc.) the rock floor of the spillway will vary between six and nine inches above or below the design grade line. The rock walls will also project about four inches above and below the design slope. Scaling geometrically this prototype roughness becomes in terms of the model scale:

1. floor, \pm (0.00833 - 0.0125) feet,
2. walls, \pm (0.0055) feet.

For complete similitude the roughness should be modeled both geometrically and dynamically. From the tables and photographs in Chow⁽⁴⁾, Mannings' "n", is estimated to be about 0.035. Chow also gives an empirical equation for estimating "n" if the absolute roughness, k, is known. Thus from the expression:

$$n = \phi \left(\frac{R}{k}\right) k^{1/6} \quad (4)$$

where: n = Manning roughness coefficient

$\phi \left(\frac{R}{k}\right)$ = a constant of about 0.0342 (Strickler's Constant)

k = absolute surface roughness

If a value of nine inches is used for k in equation (4), "n" is calculated to be 0.033 for the prototype. This value is the range of those selected from tables and photographs.

From Manning's equation based on the Froude Law the relationship between model and prototype "n" is

$$n_r = \left(\frac{L_m}{L_p}\right)^{1/6} = \left(\frac{1}{L_r}\right)^{1/6} \quad (5a)$$

$$n_r = \left(\frac{1}{60}\right)^{1/6} = 0.506 \quad (5b)$$

Using $n_p = 0.033$ ("n" for prototype)

$$n_m = 0.0165 \text{ ("n" for model)} \quad (6)$$

Now using equation (4) for the model with a model "n" of 0.0165, k_m for the model can be obtained.

$$k^{1/6} = \frac{n_m}{\emptyset (R/k)} \quad (7a)$$

$$k = 0.0127 \text{ feet for model} \quad (7b)$$

This value compares very favorably with the upper limit obtained by geometric scaling of the floor roughness. Note however that the assumption of $\emptyset (R/k)$ being equal to Strickler's Constant for the model must be made. As mentioned previously, an expanded metal lath was used to model the roughness. The metal lath was stapled to the wood channel and only the positive side of the plus or minus elevation was modeled. The exact size and shape of the two types of lath used is given below.

	<u>Lath</u>	<u>Floor</u>	<u>Walls</u>
Style Designation		1/2" No. 16	1/2" No. 18
Strand Width		0.078 in.	0.081 in.
Approximate Size of Mesh-Width		0.462 in.	0.462 in.
Center to Center of Bridges - Length		1.2 in.	1.2 in.
Strand Thickness		0.060 in.	0.048 in.
(Doubled)		0.120 in.	0.096 in.
Approximate Size of Opening		0.375 x 0.906 in.	0.392 x 0.920 in.
Percent Open Area		64 to 68%	70 to 75%

The doubled strand thickness was a good indication of the absolute roughness. In this case the floor roughness was 0.010 feet which corresponded to a prototype value of about 7-1/2 inches and within the expected roughness limits. The walls were about 5-1/2 inches rough on the prototype scale.

In any hydraulic model there are a number of limiting factors that prohibit exact geometric and dynamic similitude. These must be kept in mind at all times. Surface tension effects although minimal, are still present especially during low depth flows in the forebay area. As a consequence prototype forebay water surface elevations will be slightly lower than predicted. Also since the complete randomness of the prototype roughness can never be modeled, the simulated roughness material used is at best a good engineering approximation to the prototype. And lastly, it must always be kept in mind that viscous forces are ever present and also influencing the flow patterns to a limited extent.

V. TEST RESULTS

A. General

In order to intelligently judge the results of the model study, the criteria for good hydraulic spillway design should be clearly understood. Therefore before beginning a detailed analysis of the test results, the salient points of good hydraulic spillway design will be presented.

The purpose of any spillway is simply to safely convey flood flows around, through, or over the dam. The potential energy of water behind the dam must be safely and efficiently controlled as it changes to kinetic energy in its journey to the river downstream. The assurance of complete safety for the dam under the worst possible flood conditions is the ultimate goal for the design of any flood spillway.

In order for flow control weirs to perform as designed they must have uniform depths and velocities over their entire length. This means that great care must be taken in providing smooth entrance conditions. Inefficient weirs will result in higher reservoir surface levels than expected, resulting in less freeboard on the dam and reduced dam safety factors.

Hydraulic jumps, if used as energy dissipators must be stable and occur at the desired location. They must also be of a strong nature

if effective energy loss is to be realized. Unstable jumps cause undesirable surges and resulting shocks elsewhere in the spillway. The high degree of turbulence and bottom eddies created must occur where damage to the spillway floor surface is tolerable. Flow separated areas and their accompanying vortices are undesirable in that they reduce the efficiency or conveyance of the flow passages, resulting in higher velocities in these areas which could result in erosion.

In general, all velocities in tailwater regions and other critical areas must be low enough to prevent surface erosion. One critical area would be the flow in the forebay area past the earth dam itself. Erosion of the dam is most undesirable and dangerous.

Lastly, surface waves created downstream of hydraulic jumps should be small and steady so that resulting wave impact forces and possible erosion are insignificant.

The original spillway design as shown in Figures 3 and 4 was studied at five different flowrates. The spillway design flood of 45,000 cfs was the maximum flowrate tested and thereby designated the 100 percent flow. The other flowrates were called the 80, 60, 40, and 20 percent flows. These prototype and model flowrates are shown in Figure 17. The wide range of tests prevented any unusual quirks in spillway performance from going unnoticed. The predicted tailwater curve used in the tests is shown in Figure 18 and the first ogee rating curve is part of Figure 3. Elevations from these curves for the five flowrates studied for model and prototype are also shown on Figure 17.

Project 1050-326
Nockamixon Spillway Test Data
Model Scale 60:1

		Percent of Design Flood				
		20%	40%	60%	80%	100%
Prototype Flowrat (cfs)		9,000	18,000	27,000	36,000	45,000
Model Flowrate (cfs)		0.326	0.646	0.968	1.290	1.613
Manometer Setting Inches of Gage Fluid		0.80"	2.05"	4.20"	7.45"	11.90"
Prototype	Head Water Elev. (feet)	398.90	400.90	402.70	404.25	405.60
	Tail Water Elev. (feet)	318.30	319.45	321.14	323.23	324.90
Model	Head Water Rdg. (feet)	1.948	1.982	2.012	2.038	2.060
	Tail Water Rdg. (feet)	1.980	1.999	2.028	2.062	2.094

Note: Hook Gage Zero is 1.800 Feet

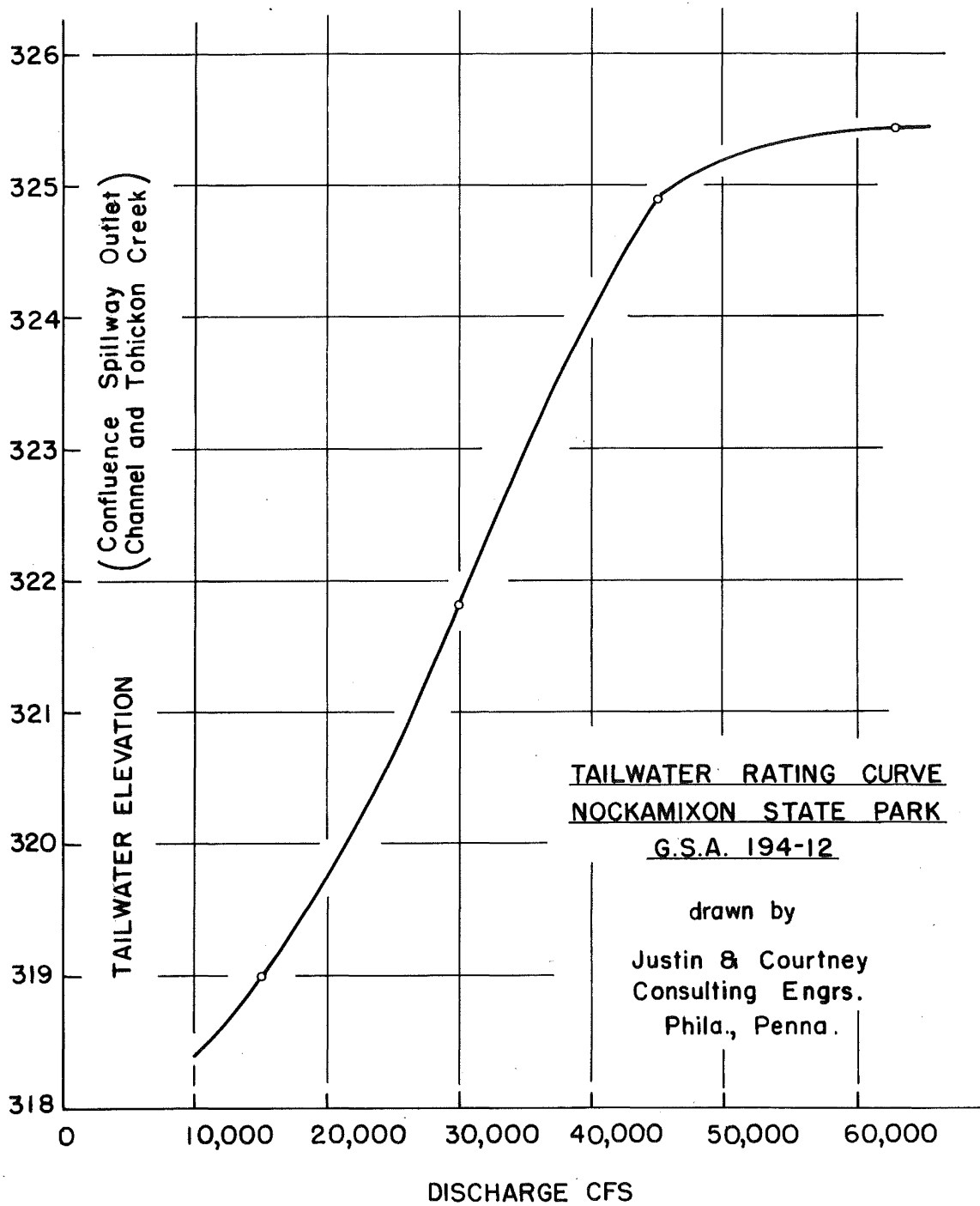


Fig. No. 18

Results of the model test for the original design are presented in a number of ways. Efficiency of the weirs and a resulting indication of upstream entrance conditions is noted by plotting the water surface profiles at the crest. Location and stability of jumps and overall uniformity of depths along with vorticity identification has been recorded by the use of water surface "contour" maps for the entire lower half of the spillway. Photographs were taken of all critical areas as a positive means of recording the exact flow patterns. Some confetti-streak photographs were also made of the forebay entrance flow patterns.

The results of the model test for the modification program are presented in the same manner as for the original design with one major exception. Only the 100, 60, and 20 percent flowrates were tested. Therefore when comparisons are made these will be the only flowrates presented. Velocity measurements were only made for the final design configuration at 100 percent design flowrate.

B. Lower Half Spillway

In order to record what occurred in this region of the spillway, the model water depths were converted to prototype scale and plotted at their location on a plan view of the prototype spillway. Interpolation was necessary to construct the one foot interval water surface contours, similar to the method used in making a topographic map of earth surface contours. These water surface contour maps serve then to show the location of the hydraulic jumps, depressed areas, vortices, stagnation areas, and wave buildup areas. In effect, an

indication of the flow-through efficiency can be obtained from the contour maps. The results of all model depth measurements made are conveniently recorded on the contour maps. The water surface contour maps for all data taken for the entire model study are assembled in the Appendices under A-1. A complete list of these contour maps appears at the front of Appendix A-1.

The model spillway as originally tested had no simulated channel roughness. This test acted as a lower bound in viewing the results of later tests with roughness added. Since a minimal amount of resulting friction and energy loss occurred with the smooth channel, this test bounded the effect of artificially adding surface roughness. A more detailed discussion of some additional and planned tests with the artificial roughness is given in a later section of Test Results. Since these smooth and rough test results are only of academic interest, the discussion of model performance will be confined to all tests with the simulated rough channel surfaces.

In general no unexpected phenomena occurred at any of the lower flowrates tested. In all cases undesirable hydraulic characteristics which occurred at 100 percent design flowrate decreased in magnitude as the flowrate decreased.

The following undesirable flow characteristics were noted for the original spillway design (see Figures A1-6 to A1-10). The first hydraulic jump although mildly strong occurred on the stilling basin floor and obliquely across the basin as shown in Figure 19 for 100 percent flow. A large vortex appeared at the inside corner resulting

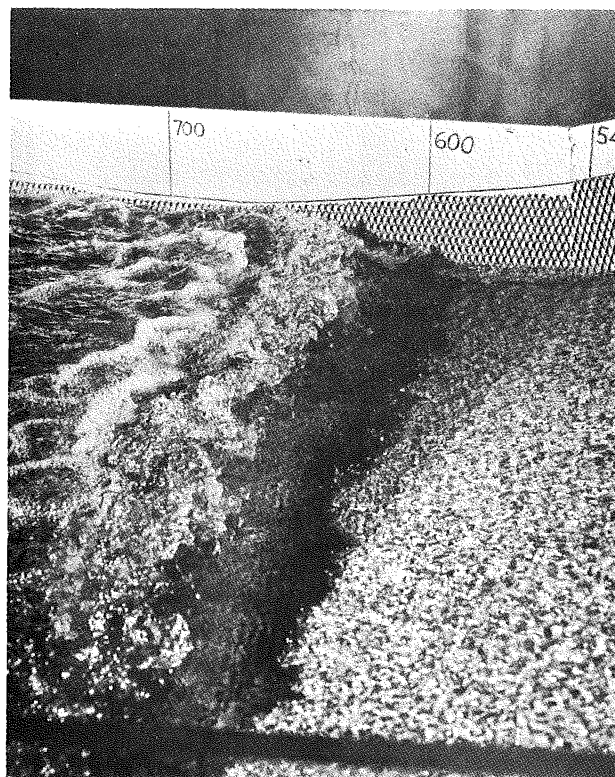


Fig. No. 19 First jump at 100% flowrate - original design

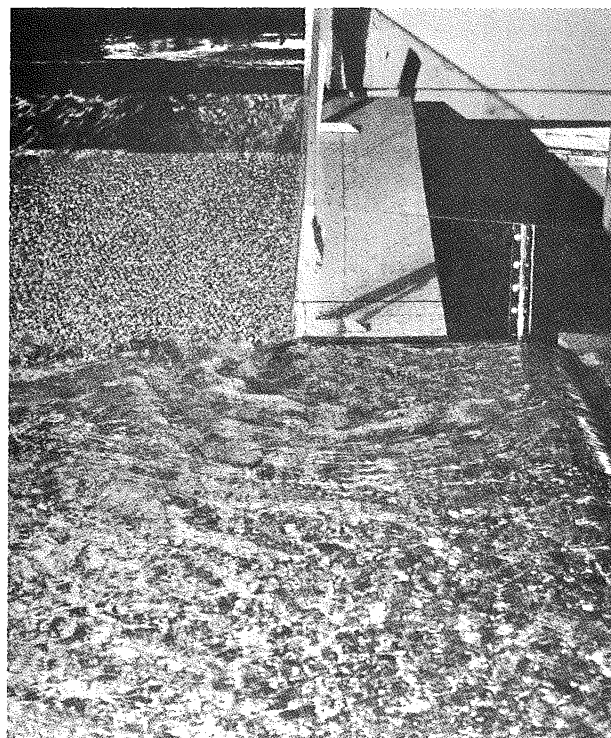


Fig. No. 20 Vortex at inside corner with 100% flowrate - original design

in a depressed region. (Figure 20). This vortex also caused the flow over the second ogee weir to fluctuate approximately four feet in depth at the worst condition. At the outside corner a pile-up took place resulting in a net elevation difference of twelve feet over the first stilling basin. The second hydraulic jump was very weak (undulating), slightly oblique, and even partially submerged as shown in Figure 21 for 100 percent flowrate. The conditions at the second jump for 20 percent flowrate are shown in Figure 22. The surface contour maps in the Appendix for the original design also reveal the unevenness downstream of the second jump for all flowrates.

Undesirable hydraulic conditions were improved considerably in the first stilling basin after modification Part A was made on the model. These results can be seen in Figures A1-11 to A1-13 in the Appendix. However, there was not a great deal of difference in hydraulic performance between Part A and Part B of the modification program to warrant detailed discussion. Conditions remained poor downstream of the second weir after the first modification.

After the second modification was made (as shown in Figures 9 and 10) all undesirable flow characteristics that were associated with the original design were either considerably improved or completely eliminated. As shown in Figures A1-14 to A1-16 of the Appendix the first hydraulic jump started on the slope and ended before the flow passed around the corner as a result of moving the north side wall fifty feet. This modification along with the thirty foot inside radius, completely eliminated the vortex from forming at this location for all flowrates. The location and vigor of the first jump and elimination

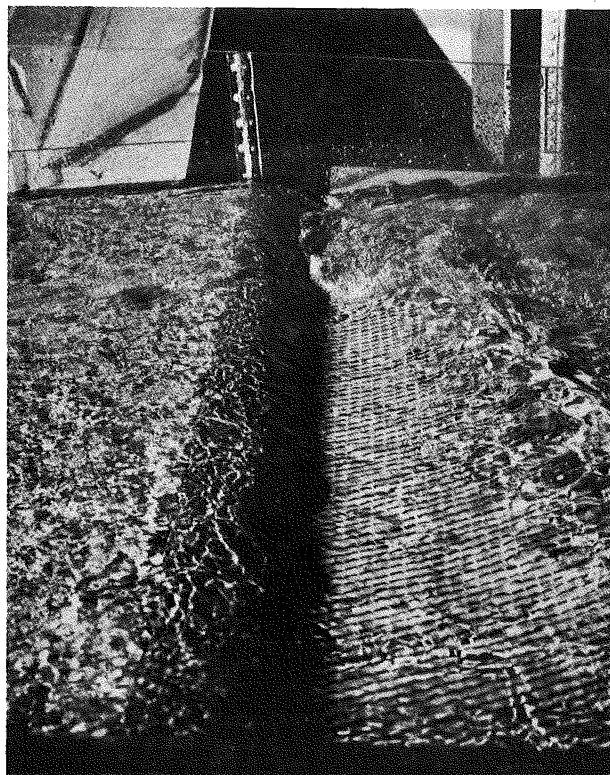


Fig. No. 21 Second jump at 100% flowrate - original design

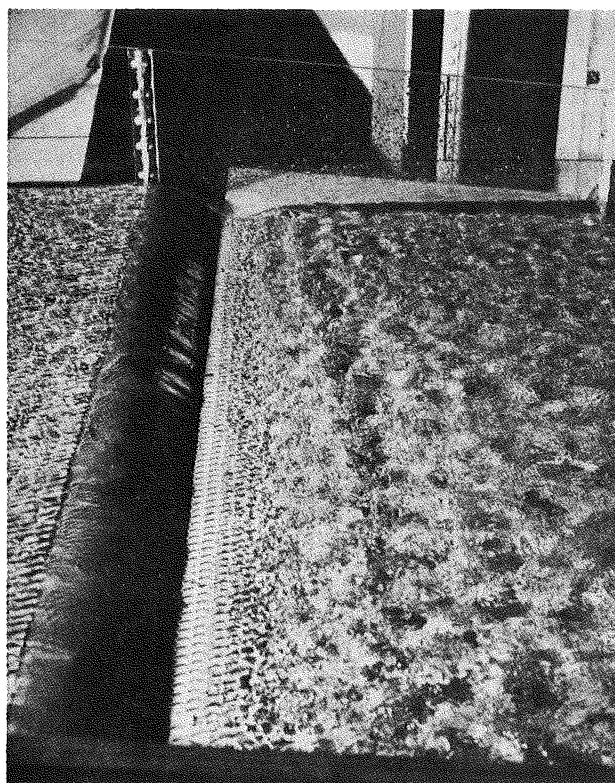


Fig. No. 22 Second jump at 20% flowrate - original design

of the large vortex can be seen in Figures 23 and 24 for the 100 percent flowrate. The same phenomena at 20 percent flow are shown in Figures 25 and 26. There was practically no bulking at the outside corner after the large radius was installed and the depth only varied by seven feet (prototype) over the entire length of stilling basin. The second jump although completely submerged was much stronger and very uniform across the channel. Figure 27 shows the second jump with normal tailwater and 100 percent flowrate. By lowering the tailwater it was found that the second ogee jump was completely swept out at a tailwater elevation of 321.1 feet. The water surface contour maps also show the extremely smooth tailwater surface area with the final design. To facilitate the comparisons between the original and final designs, Figure 28 was prepared for 100 percent flowrate. The outline and surface contours of the original design are shown by the dotted line.

C. Weirs and Forebay

By measuring the model water depths at closely spaced increments along the weir crest centerline, a section view of the water surface profile for each weir was obtained. These sectional views for all flowrates and conditions studied are compiled in Appendix A2. If uniform velocity distribution is assumed over the crest length, an ideal weir will then have a uniform depth of flow over its entire length. The criteria for good forebay and spillway design was therefore to determine how close the weir cross sections came to being uniform over the entire length of crest.



Fig. No. 23 First jump at 100% flowrate - final design

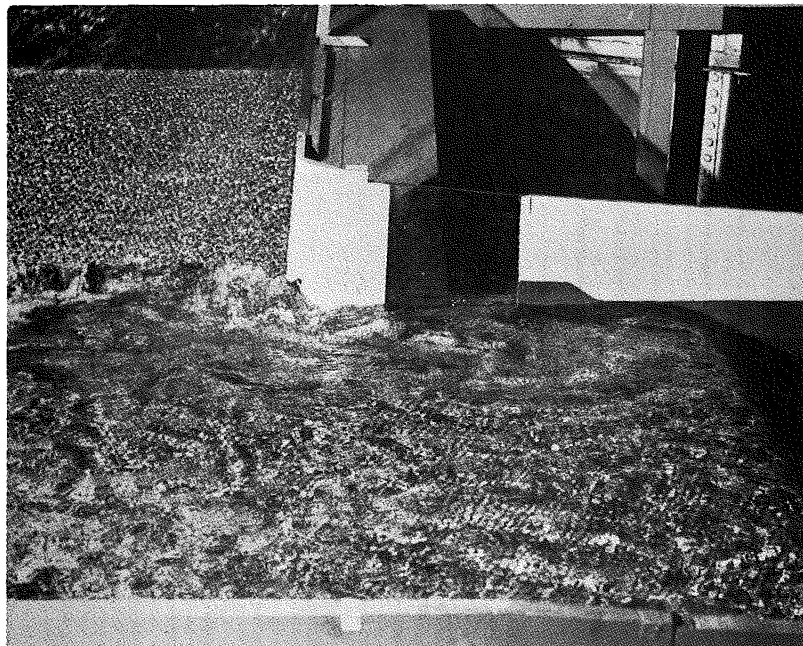


Fig. No. 24 Elimination of vortex - final design at 100% flowrate

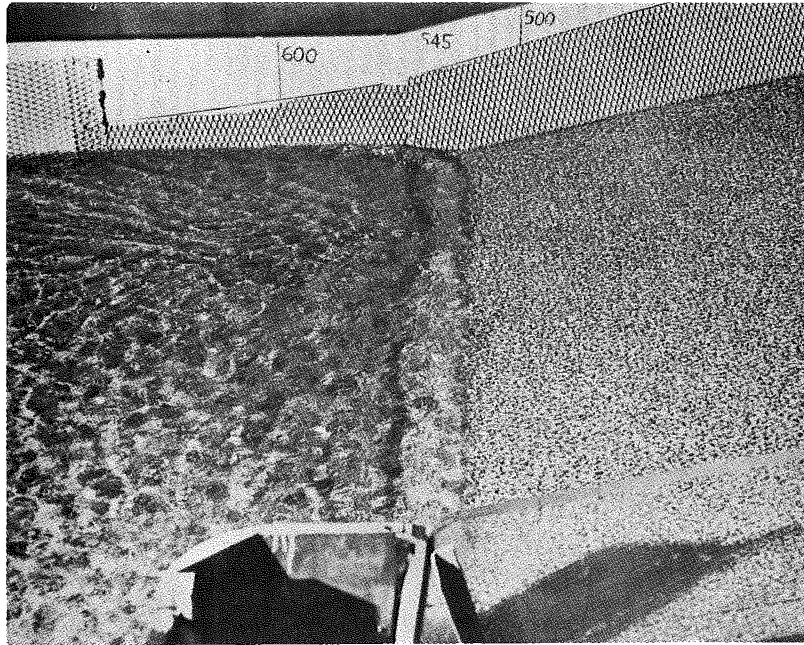


Fig. No. 25 First jump at 20% flowrate - final design

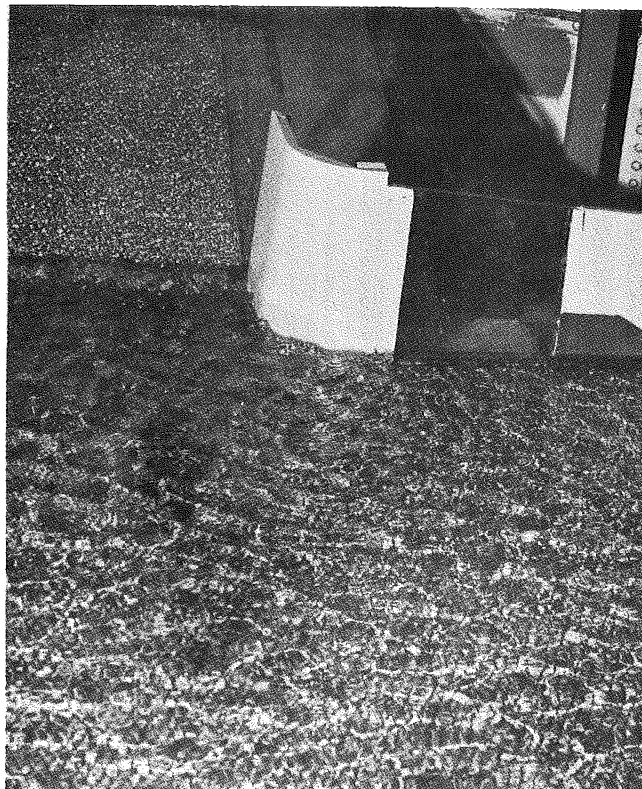
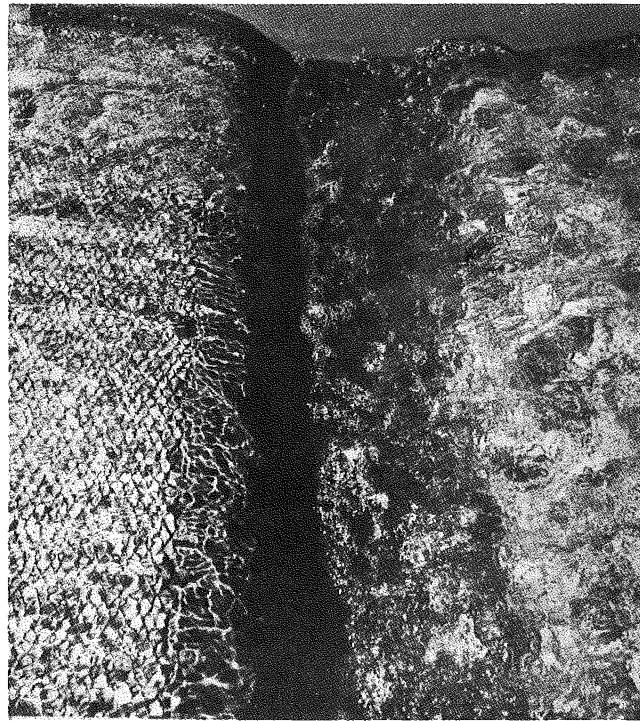


Fig. No. 26 Elimination of vortex - final design at 20% flowrate



(a) Facing south wall

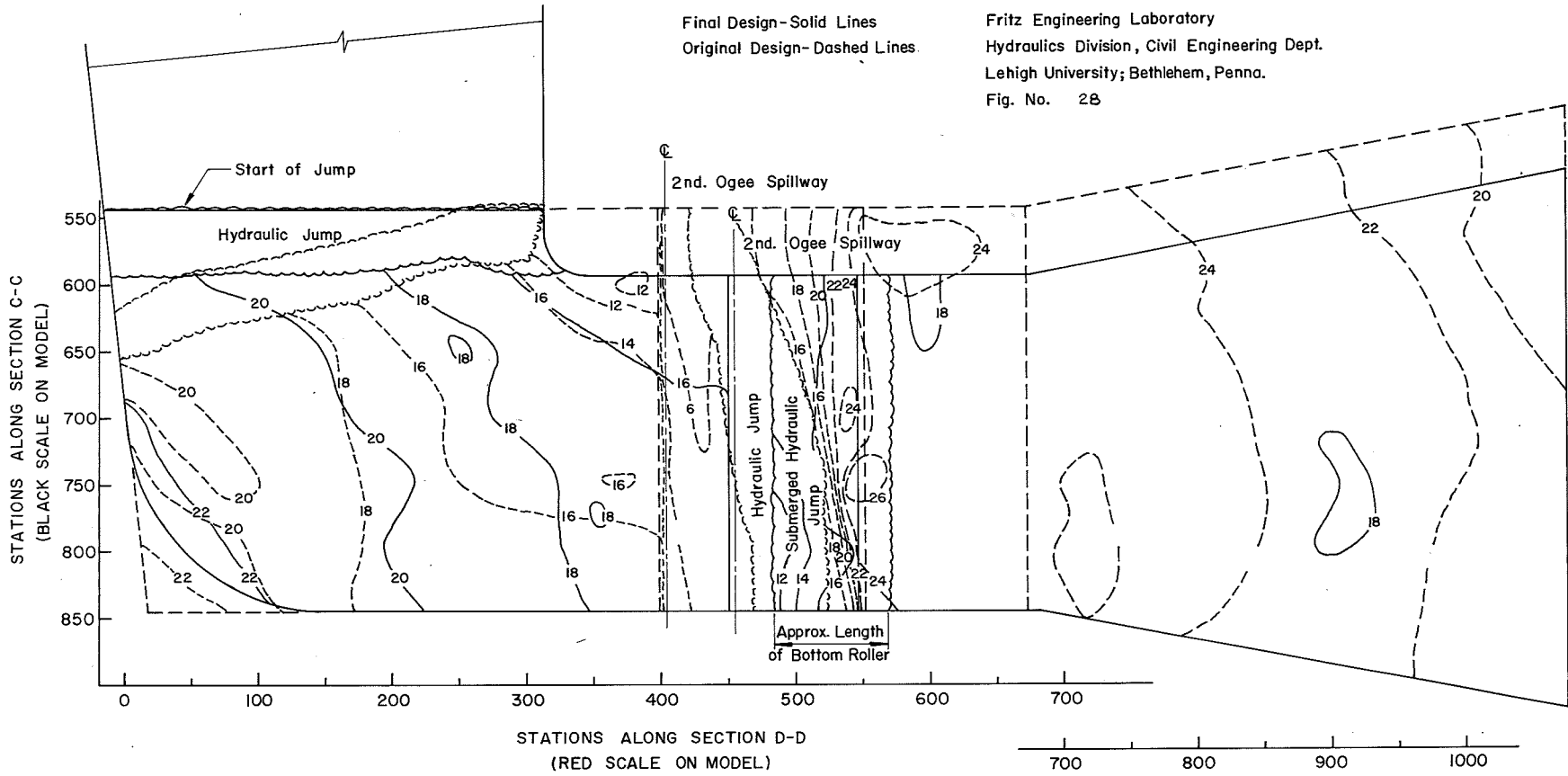


(b) Facing north wall

Fig. No. 27 Second jump at 100% flowrate -
normal tailwater - final design

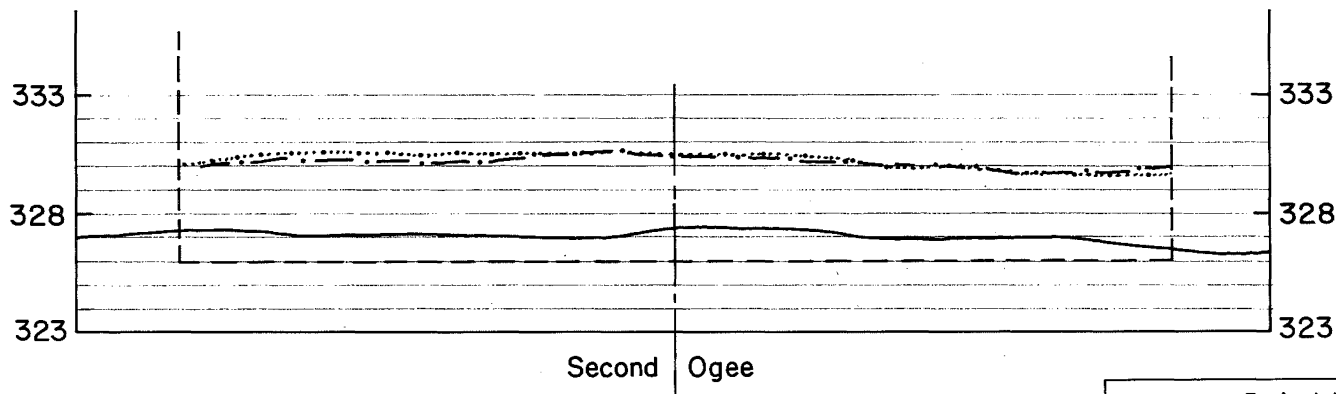
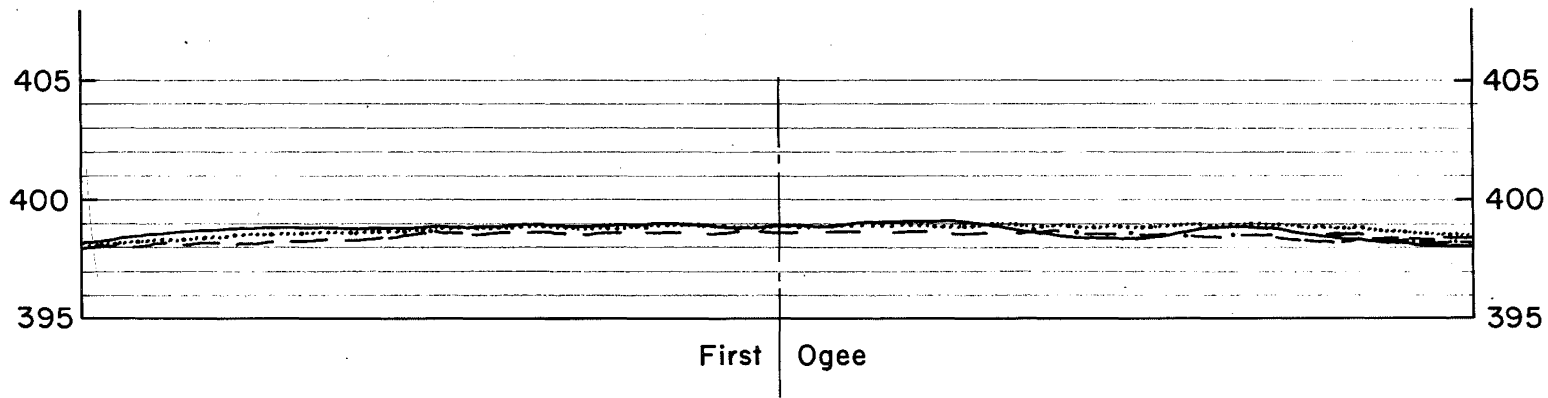
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 NOCKAMIXON SPILLWAY MODEL
 Original vs. Final Design
 Percent Design Flow : 100 %

Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. 28



In order to easily compare the results for all forebay and spillway modifications, Figures 29, 30, 31 were prepared for 20, 60, and 100 percent design flowrates, respectively. No large differences were evident at the 20 percent flowrate for either the first or second ogee. However, improvement in the flow patterns over the second weir is quite apparent at the other two flowrates. At 100 percent flowrate the depth varied from eleven to four feet over the crest or a difference of seven feet for the original design. The final design varies only four feet from eleven to seven on the crest. (Note that the "super-elevation" effect for flow around an open channel corner is still apparent in the final design). This same improvement can also be seen for 60 percent flow in Figure 30.

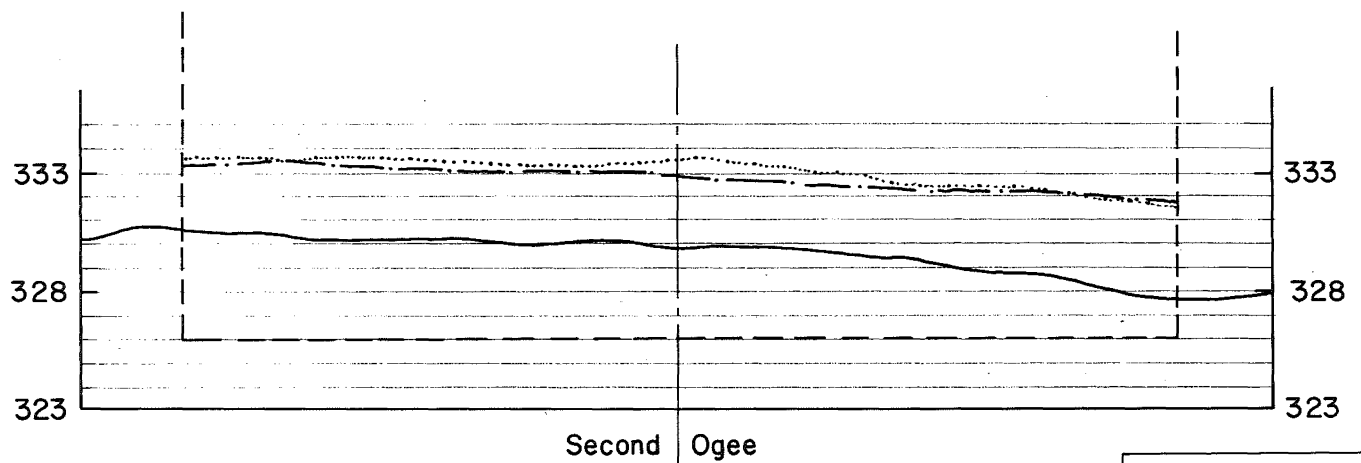
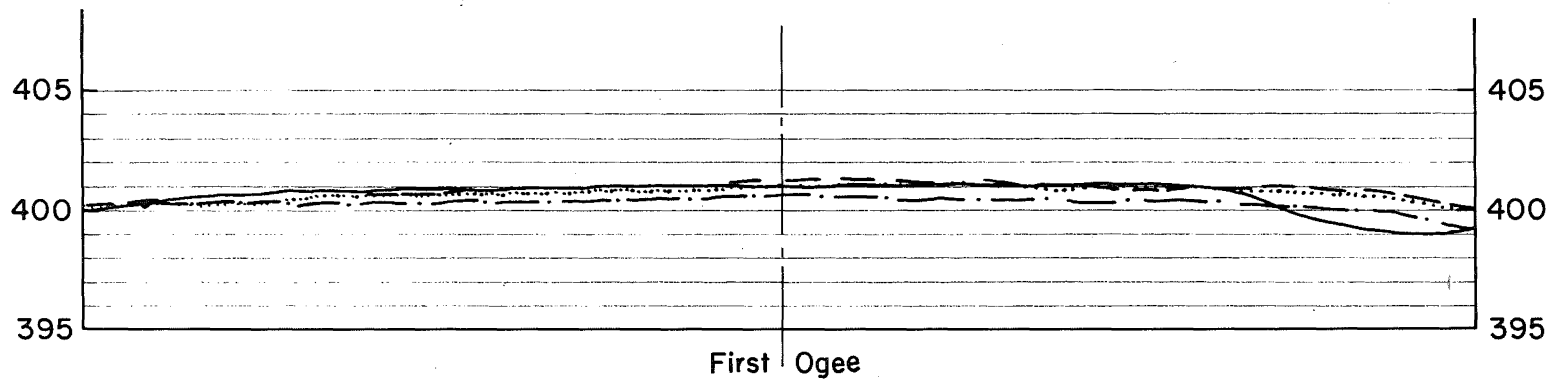
Comparisons of forebay modifications for the flow over the first ogee can also be readily made in these figures. Once again the 20 percent flowrate shows little differences. The large improvements made on the east side (facing upstream) by the forebay modifications are quite evident in Figure 31 for 100 percent flow. It can also be seen that although impractical from a constructional point of view, Modification No. II (dotted line) gave the best profile on this side. In Modification No. III there was slightly more of a dip in this area. However, because of construction ease, Modification No. III became the final design configuration. As shown in the time-streak photographs taken (Figure 32) the water approached the spillway on the east side along a line parallel with the dam axis. This resulted in a buildup in the center of the first weir with a depressed area on the east side (facing downstream). The small berm on this left side in the original



Both Views Looking Upstream

- Unmodified Original Design
- - - Forebay Mod. I Original Design
- Forebay Mod. II Mod. Part A
- · - · Forebay Mod. III Final

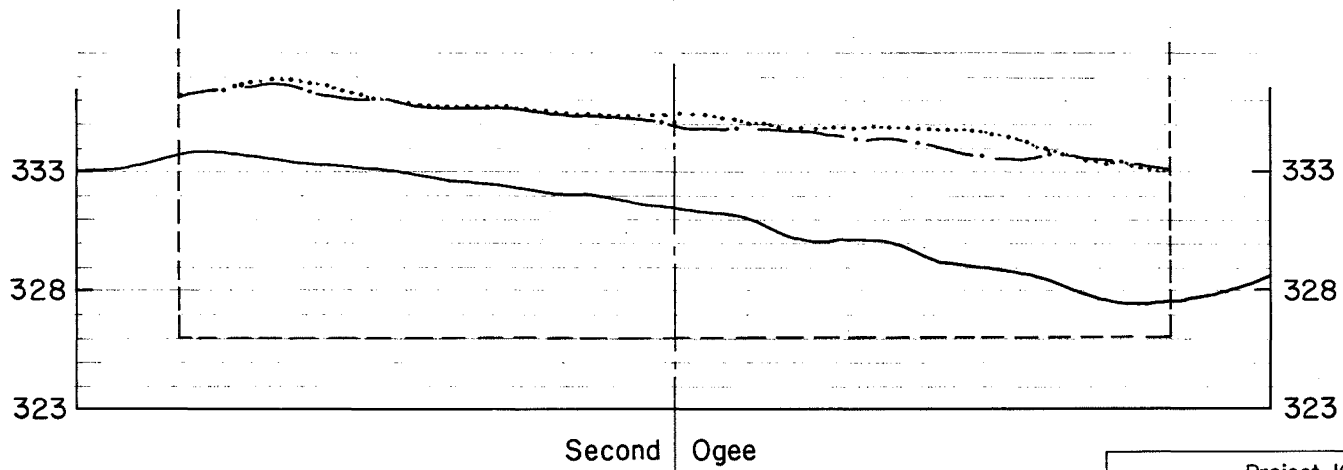
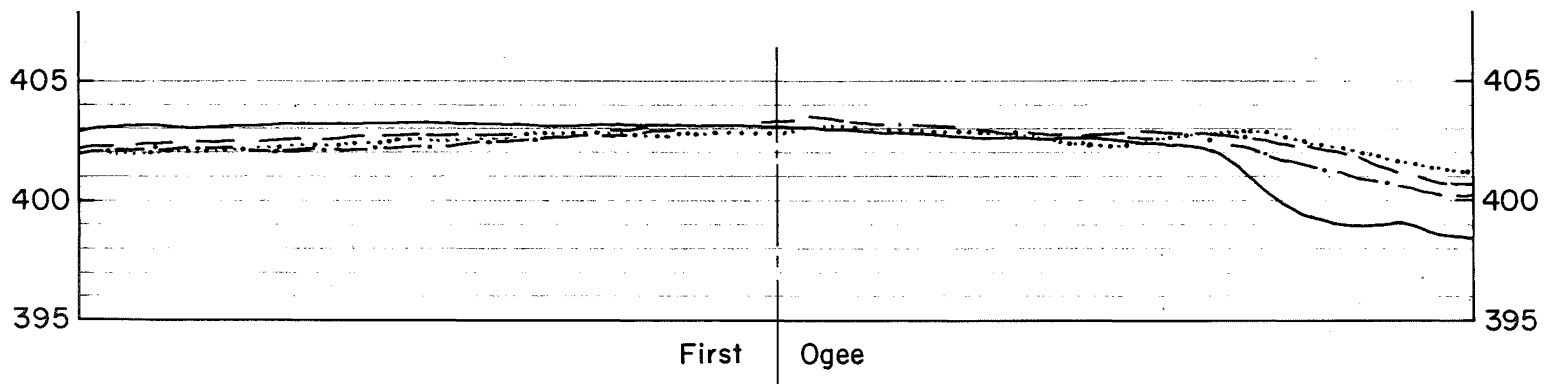
Project I050-326
 NOCKAMIXON SPILLWAY MODEL
 Weir Cross Section Comparisons
 Design Flow - 20 %
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. 29



Both Views Looking Upstream

- Unmodified Original Design
- - - Forebay Mod. I Original Design
- Forebay Mod. II Mod. Part A
- · - Forebay Mod. III Final

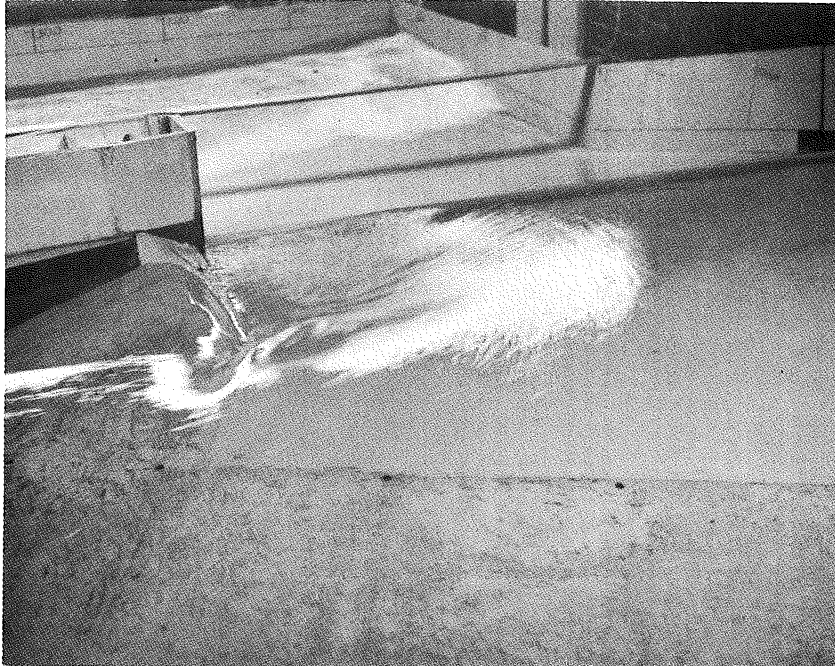
Project I050-326
 NOCKAMIXON SPILLWAY MODEL
 Weir Cross Section Comparisons
 Design Flow - 60 %
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 Hydraulics Division ; Civil Engineering Dept.
 Lehigh University ; Bethlehem , Penna.
 Fig. No. 30



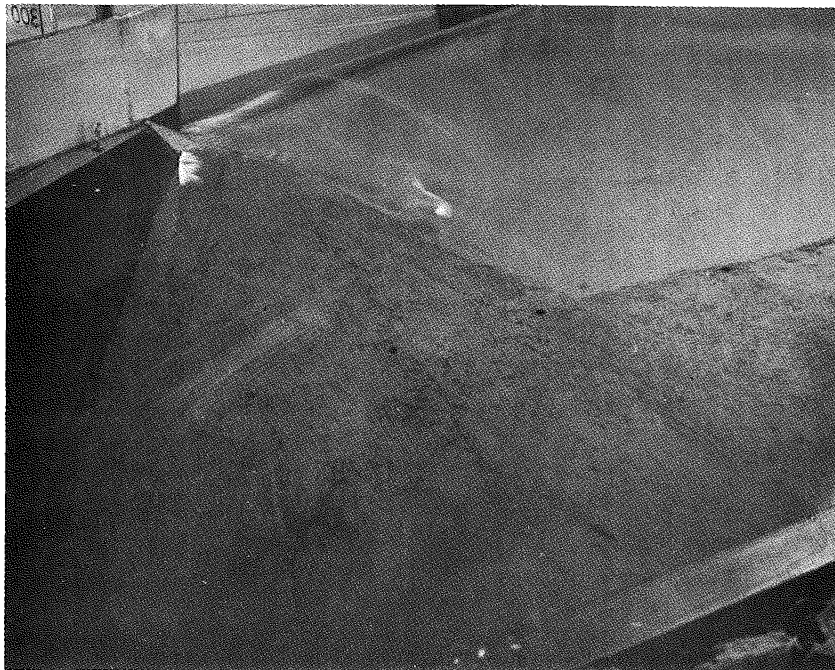
Both Views Looking Upstream

- Unmodified Original Design
- - - Forebay Mod. I Original Design
- Forebay Mod. II Mod. Part A
- · - Forebay Mod. III Final

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 Weir Cross Section Comparisons
 Design Flow - 100%
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 Fig. No. 31



(a) Depressed region in flow over first weir



(b) Time-streaks show flow entrance pattern resulting in depressed area at left over weir

Fig. No. 32 Original forebay with smooth floor at 100% flowrate

design also caused a small hydraulic jump to form (Figure 32a). The objects of the forebay modification program were therefore to streamline the flow patterns and to reduce the dip on the east side of the weir and to minimize the boundary disturbances along the dam structure. The results of flow improvement over the first ogee weir have already been discussed.

In Figure 33b the patterns along the boundary of the first modification are evident. Although the hydraulic jump is no longer present there was considerable "backup" behind the modification resulting in a deep drop in surface level around the tip (arrow) of forebay.

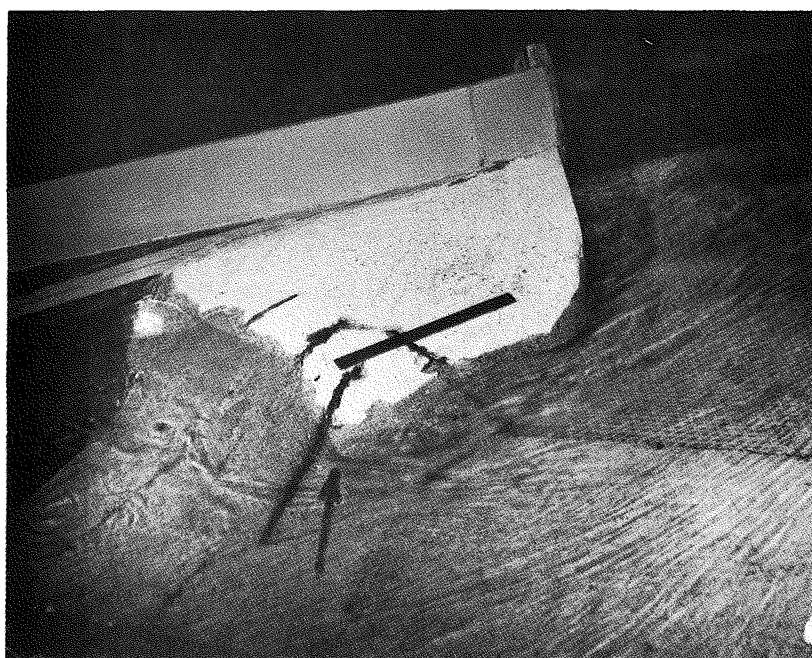
By adding more fill material the "S" flow pattern around Modification No. I was improved and a more streamlined flow around Modification No. II was obtained (Figure 34).

Figures 35 and 36 show surface patterns around the final design at 20 and 100 percent flowrates respectively. The 20 percent flowrate (approximately the 200 year flood) showed an extremely smooth surface profile around the modification. At 100 percent the surface was considerably rougher and some drop in surface elevation occurred. Some of the backup behind the modifications for all those tested was felt to be due to the proximity of the inlet rock baffle to the edge of the modification structure. Thus it is expected that the prototype will experience a far lesser drop in surface elevation at this point.

Forebay surface elevations were measured for all tests by the hook gage with inlet located at approximately the spillway centerline

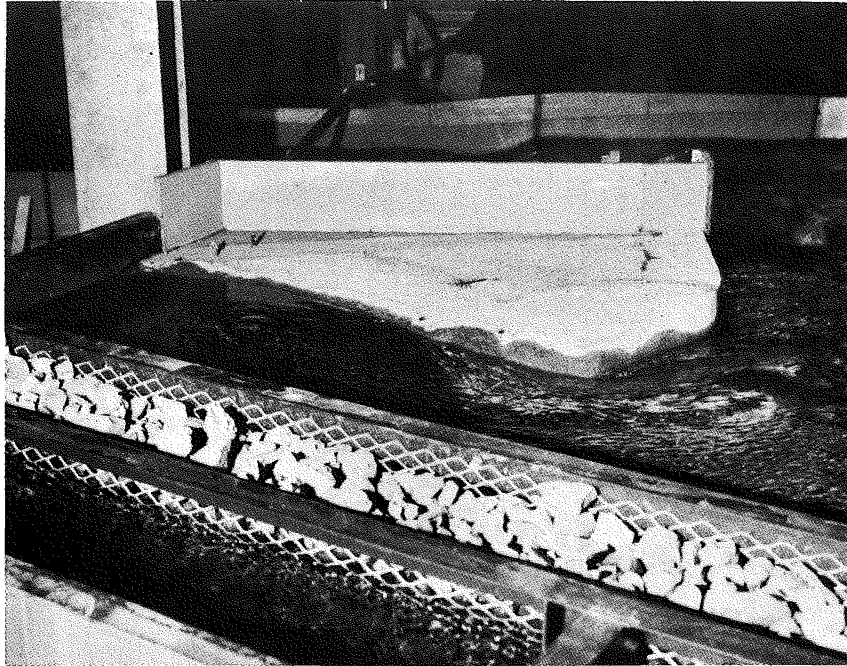


(a) At 20% flow extremely uniform around modification structure

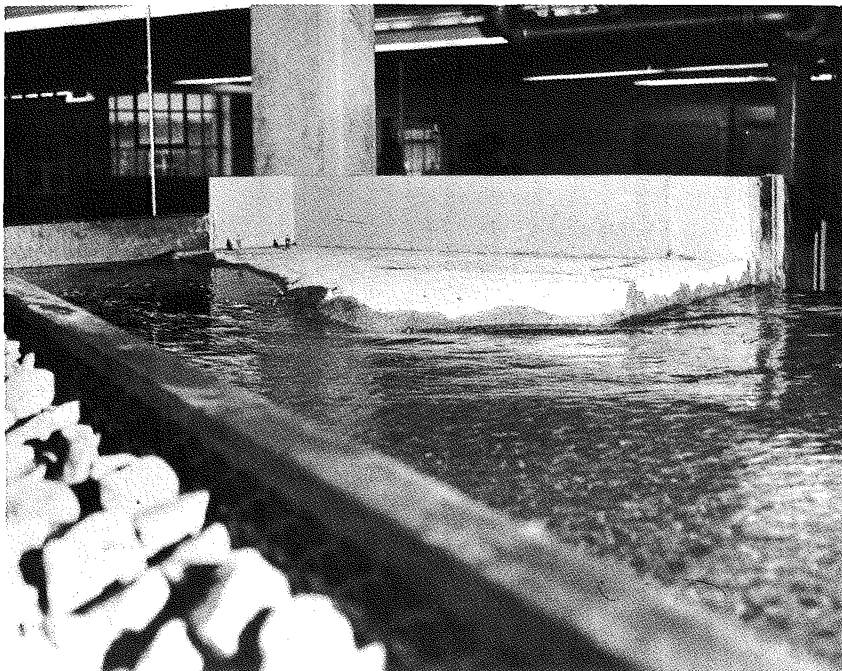


(b) At 100%, dam addition caused "S" flow pattern resulting in large surface dip at tip of modification (arrow).

Fig. No. 33 Forebay Modification No. I

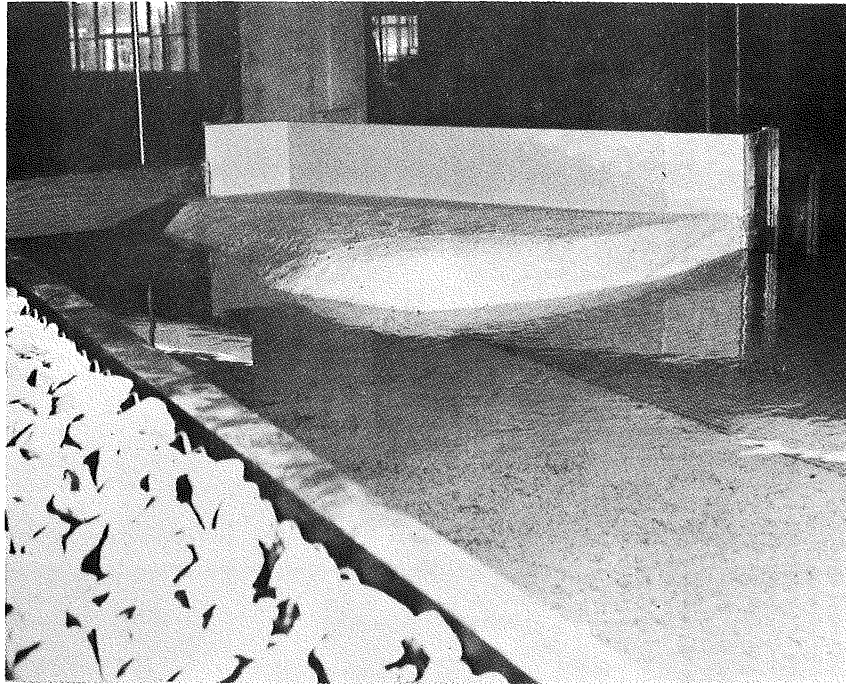


(a) Flow has more uniform approach around modified area

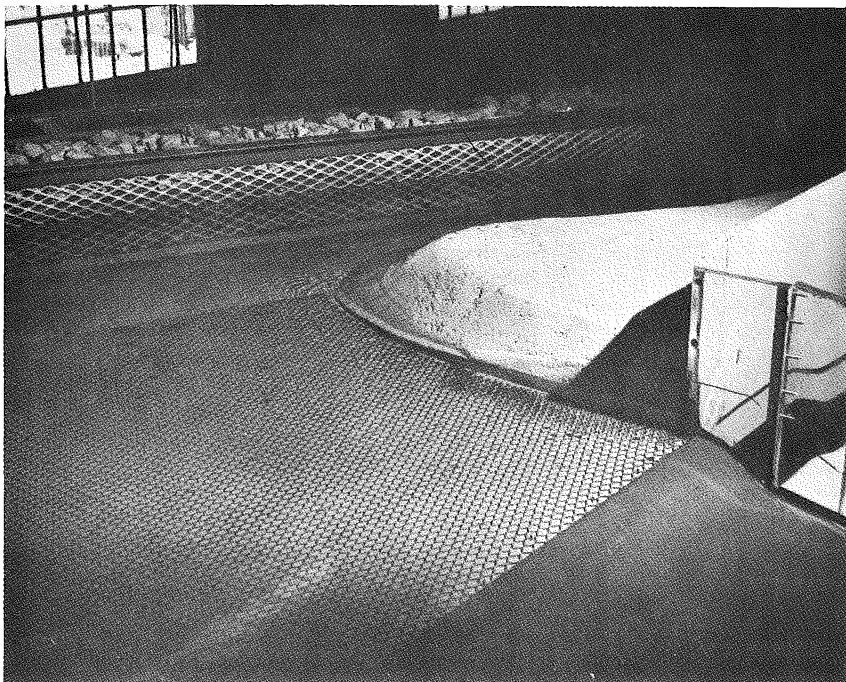


(b) Bulking behind modified area causes some drop down in surface elevation.

Fig. No. 34 Forebay Modification No. II at 100% flowrate

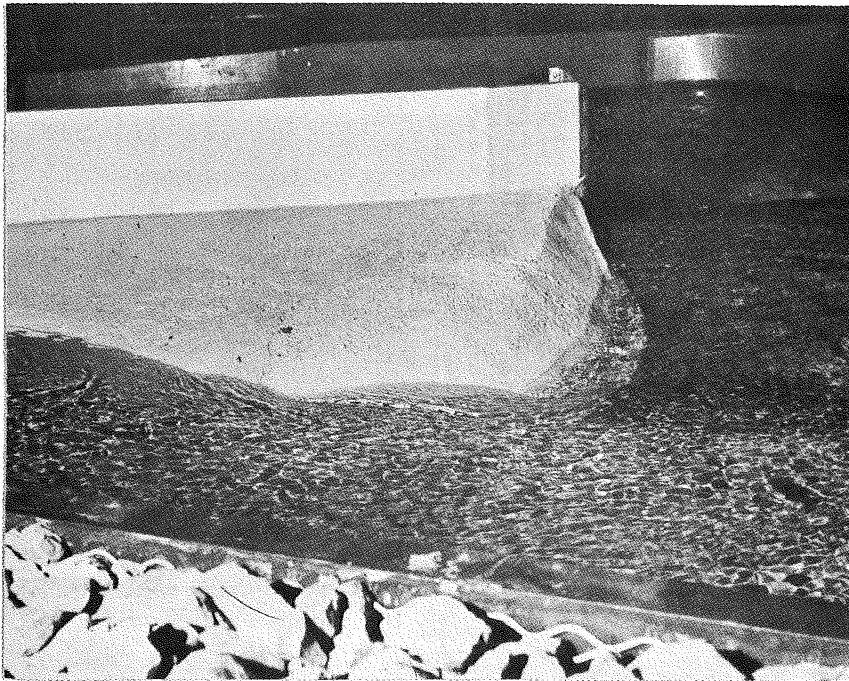


(a) View of extremely tranquil surface profile at this flowrate.

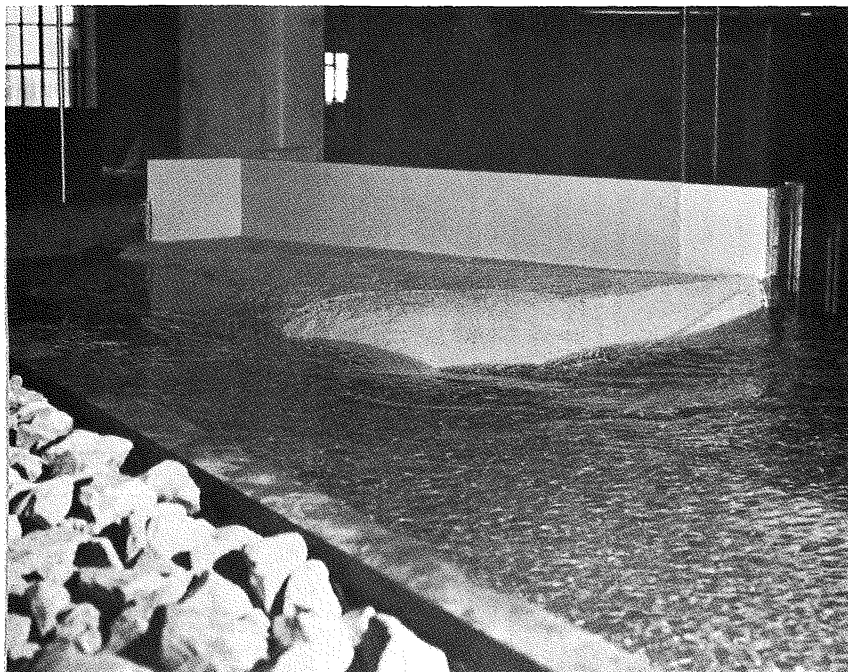


(b) View upstream of flow around modification

Fig. No. 35 Forebay Modification No. III (final) at 20% flowrate



(a) View partially downstream - some surface irregularities still present around modification.



(b) View of drop down in surface elevation at modification

Fig. No. 36 Forebay Modification No. III (final) at 100% flowrate

at the 390 floor elevation. (Figure 5). The resulting prototype elevations were plotted against flowrate in Figure 37. Also shown is the Consulting Engineers' predicted spillway rating curve. At the higher flowrates, all tests were in fair agreement with the predicted curve except for Modification No. I. The hook gage was believed to be in error in zero reading for this test. At the lower flowrates surface tension may account for some of the increase in surface elevation from that predicted.

D. Miscellaneous Results

1. Retaining wall profile

As an aid in design of the left side concrete retaining wall a water surface level profile was constructed for the final design at 100 percent flowrate. (Figure 38).

2. Velocities

As requested by the Consulting Engineers, model velocities were measured for the final design configuration at 100 percent flowrate. Only those areas of critical interest were investigated. As shown in Figure 39 the maximum velocity around the edge of the forebay modification was found to be about 23 ft/sec (prototype scale). In the tailwater area a maximum of about 11 ft/sec was measured. These velocities are felt to be very reasonable and should not result in erosion in these areas, provided the rock fill is used to protect the embankment.

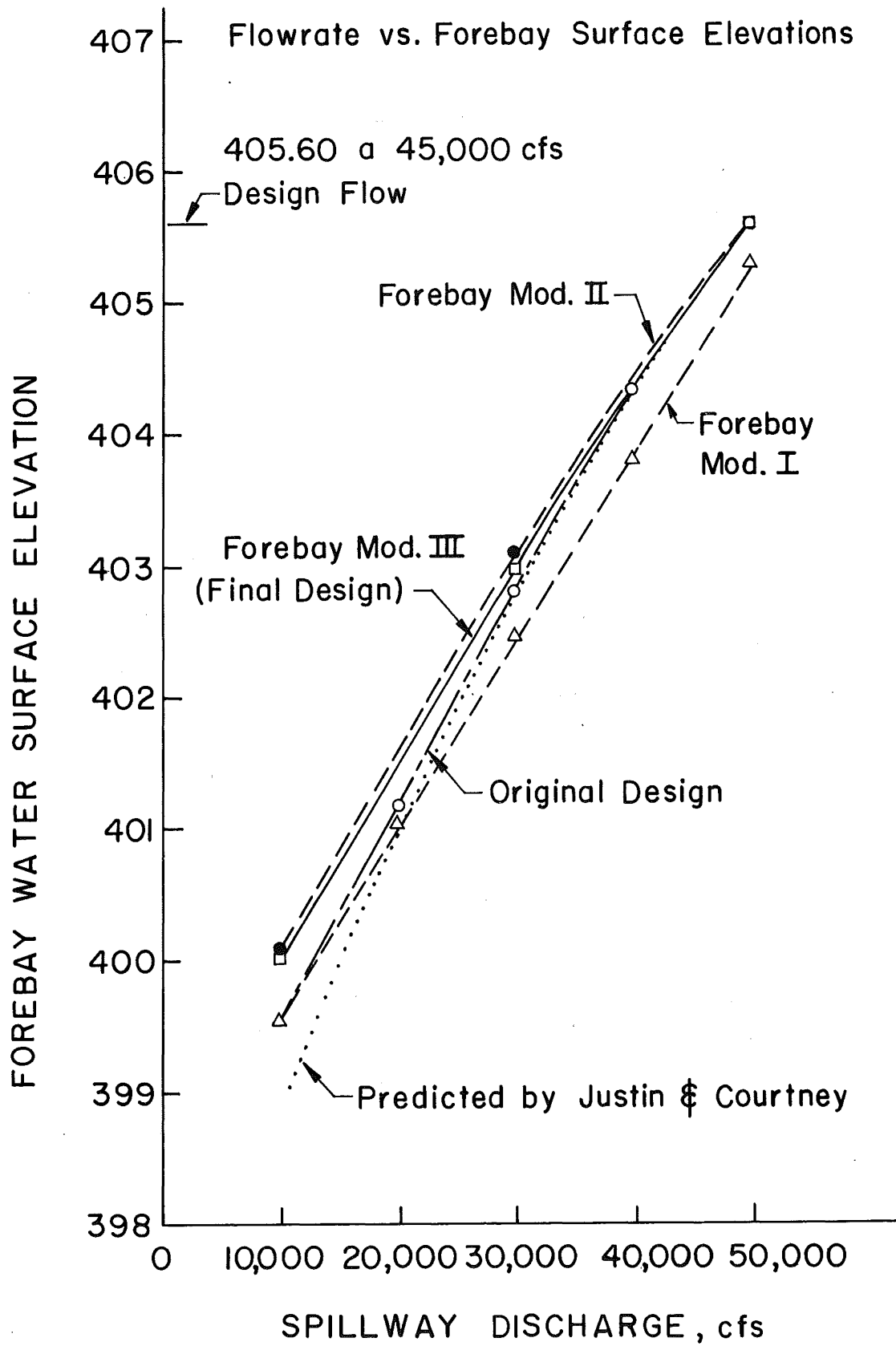
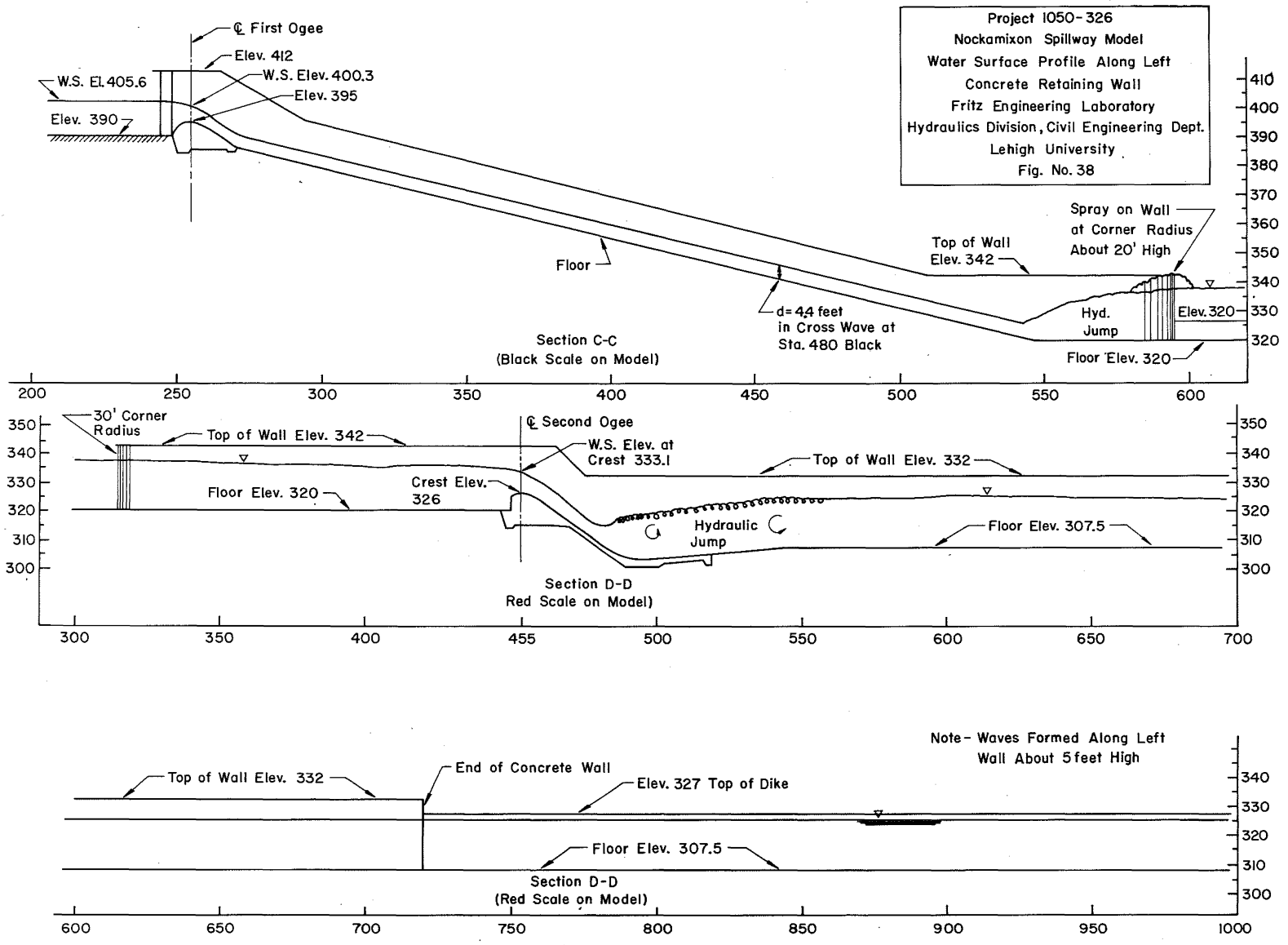
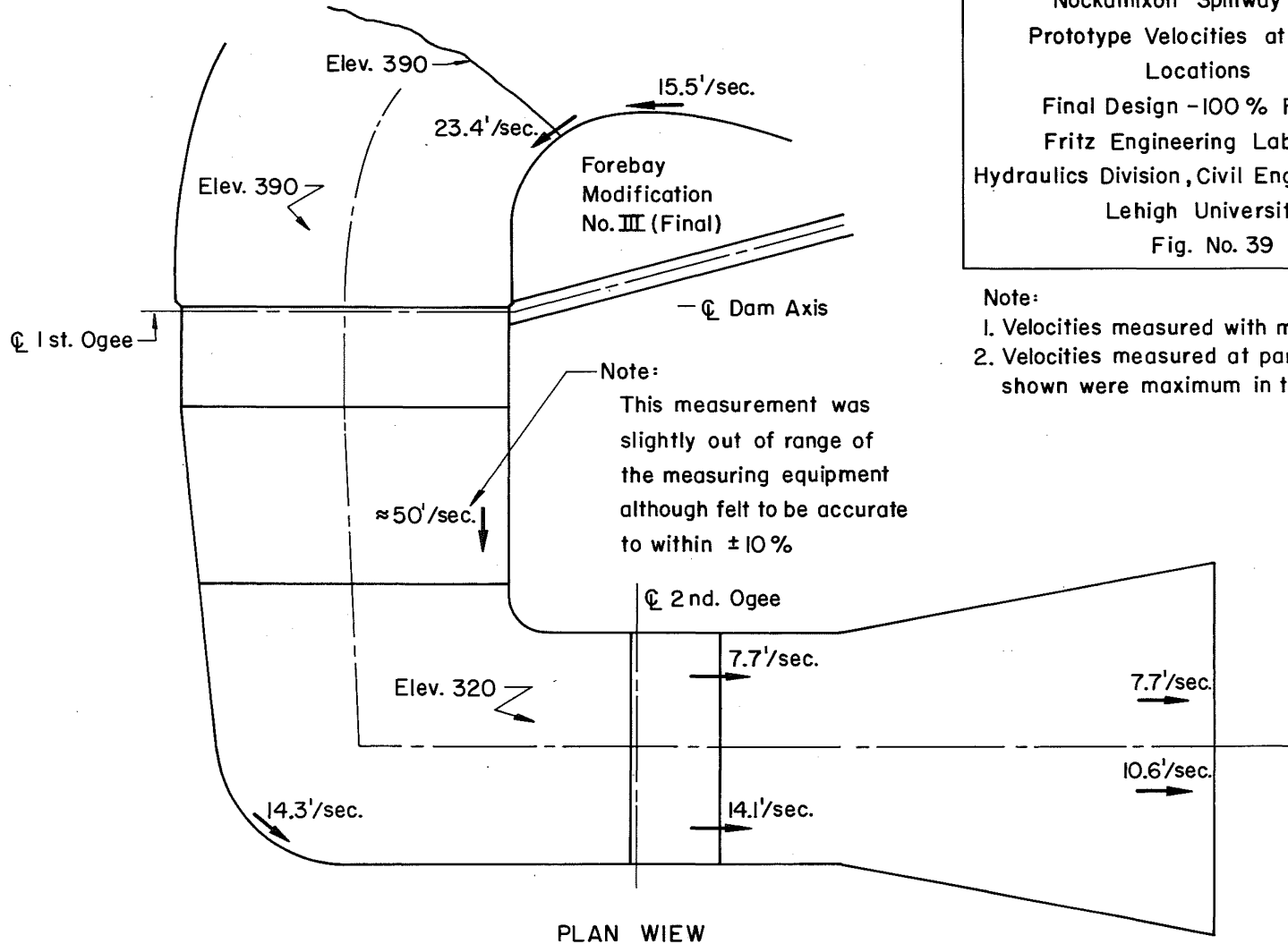


Fig. No. 37



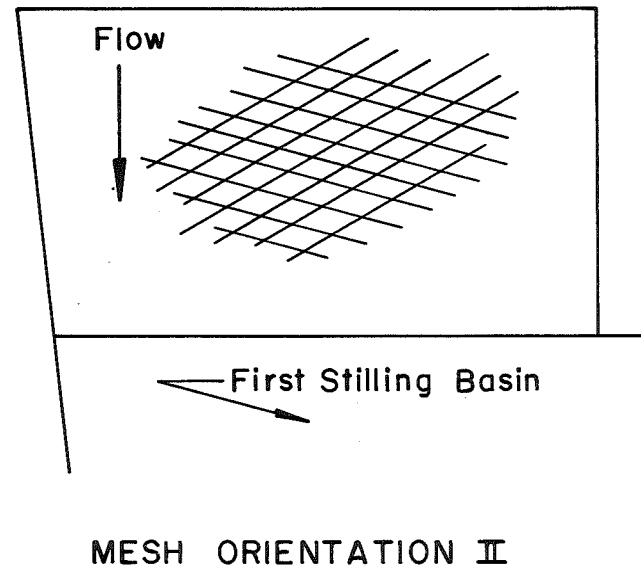
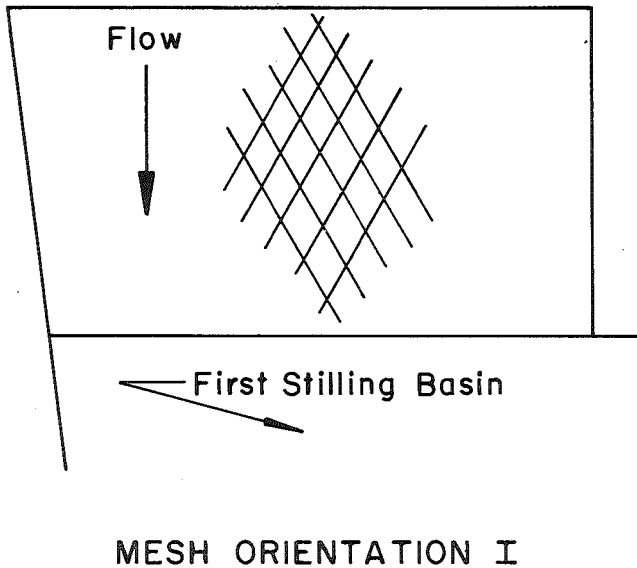
Project 1050-326
 Nockamixon Spillway Model
 Prototype Velocities at Critical
 Locations
 Final Design - 100 % Flowrate
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University
 Fig. No. 39



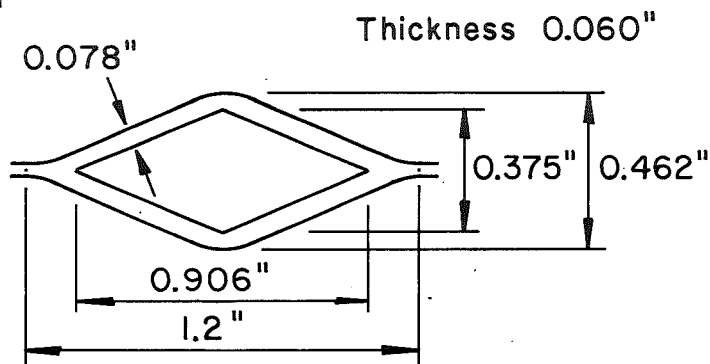
Note:
 1. Velocities measured with midget current meter.
 2. Velocities measured at particular cross section shown were maximum in that area.

3. Channel Roughness

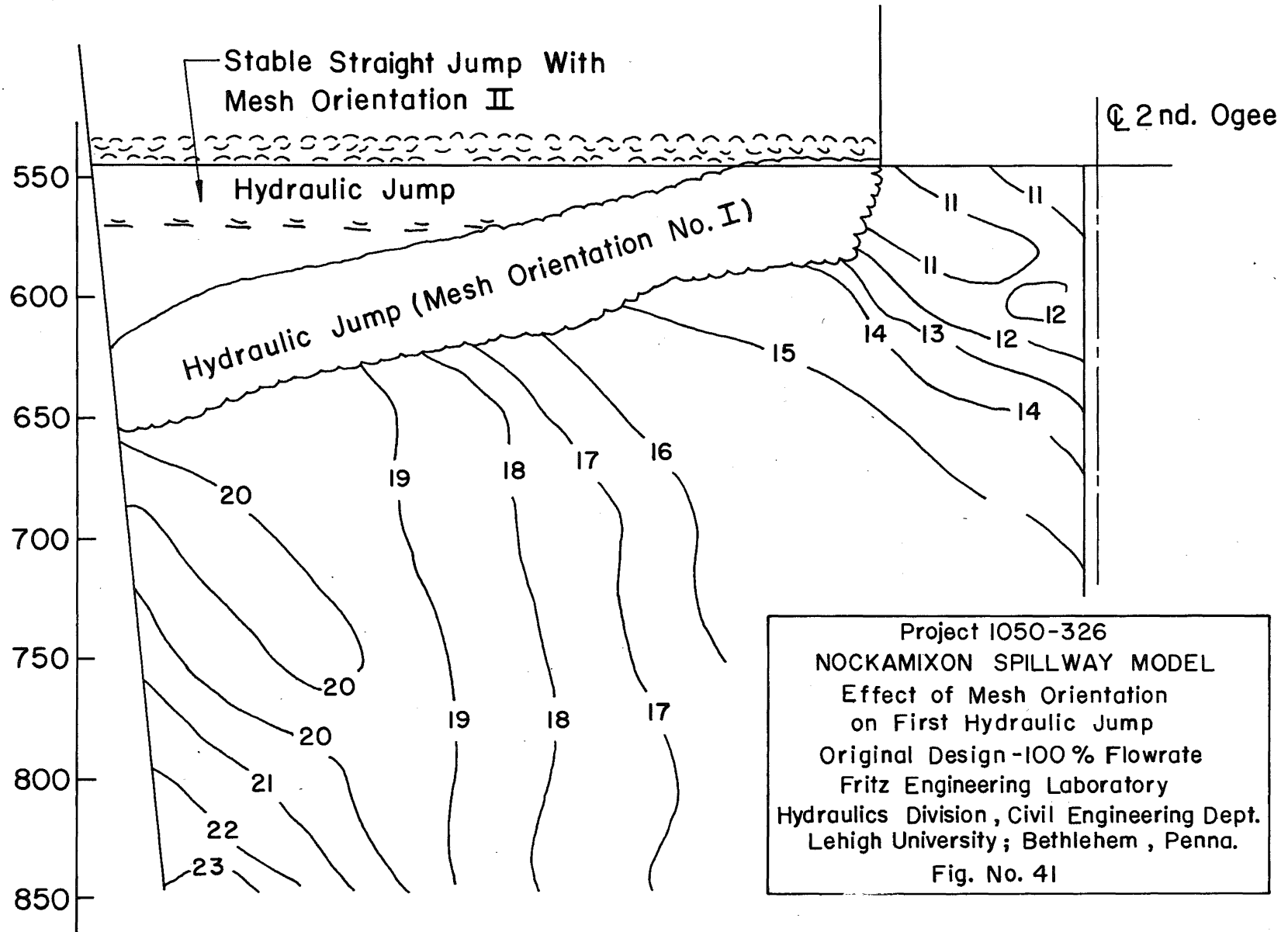
As mentioned previously the original model design was tested first without simulating the roughness to determine the upper bound on the worst possible spillway performance (least natural energy dissipation due to roughness). The size of wire mesh was then determined and installed in the model. This was mesh orientation No. I and was installed with the long dimension of the diamond in the direction of the flow on the sloping section of the spillway (Figure 40). The location of the hydraulic jump in the first stilling basin has been shown in Figure A1-10 and is reproduced in Figure 41. To determine the effects, if any, of the orientation of the diamond pattern in the mesh, orientation No. II was set-up in the model as shown in Figure 40. The location of the resulting first hydraulic jump for 100 percent flowrate has been superimposed on the original orientation in Figure 41. The jump now occurs straight across the channel and starts on the sloping section well ahead of the original jump location. Thus mesh orientation No. II resulted in improved channel performance. Undoubtedly channel hydraulic performance could be improved even further by decreasing the size of the mesh opening (increasing number of roughness elements). Therefore it may be assumed that mesh orientation No. II placed an upper bound on channel performance. Since channel roughness modeling could not exactly duplicate the prototype roughness, anyway, it was felt that by using roughness orientation No. I for all model tests, the results obtained would lie somewhere between a smooth channel and extremely rough channel and therefore be somewhat representative of what degree of roughness might be experienced on the prototype.



Note: Mesh Orientation I - Long Mesh
Dimension Runs Parallel to
Direction of Flow
Floor Mesh



Project I050-326
NOCKAMIXON SPILLWAY MODEL
Mesh Orientation
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Fig. No. 40



In this regard, the area of roughness modeling in relation to the Manning's "n" will be the topic of a Master's Thesis by one of the co-authors, Paul D. Erfle.

VI. SUMMARY OF RESULTS
AND CONCLUSIONS

By way of summarizing the model test results, the reader is again referred to Figures 28 and 31. In general, all those salient features of good hydraulic spillway design which were found lacking or worthy of improvement in the original design were incorporated in the final design. Both weirs were much improved in efficiency as measured by uniform depths over their lengths. Both hydraulic jumps were "straightened out" and located in better positions in the spillway. The energy dissipation of the second jump was much improved over the original design. The flow separated areas and accompanying vortices were eliminated in the final design. This provided more efficient flow passage through the spillway. Surface waviness, especially in the north side tailwater region was also improved by the final design.

Velocities were found to be sufficiently low in critical areas to minimize erosion.

In summary, therefore, it was felt that the model study accomplished the purpose for which it was intended by:

1. Checking the overall hydraulic flow patterns in the originally, uniquely designed spillway and finding them unsatisfactory, modifying the spillway design until good hydraulic performance was achieved.

2. Providing the necessary design information to adequately specify concrete linings, wall heights, protective dikes, etc.

3. Insuring the ultimate safety of the dam under the worst flood conditions.

However, besides accomplishing these intended purposes, the model study also enabled the design engineers to reduce the cost of the prototype structure to such an extent that more than the cost of the model itself will be saved in construction costs.

In conclusion it is felt that the prototype spillway structure if constructed to the final design configuration and with the design information provided from the model study will adequately handle the Standard Project Flood expected in the area. Therefore, also adequately protect the dam from failure by this flood.

VII. A C K N O W L E D G M E N T S

The cooperation and assistance of the following people and their organizations involved in the project are gratefully appreciated.

Mr. C. H. McConnell, Chief Engineer and the Staff
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Waters

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Mr. J. J. Williams, Justin and Courtney, Consulting
Engineers, Philadelphia, Pennsylvania

Mr. C. Lynn and his Staff of Bethlehem Pattern and
Model Shop, Bethlehem, Pennsylvania

Mr. W. Miller and his Staff, Department of Building
and Grounds, Lehigh University

Appreciation is also extended to Dr. John R. Adams for his timely hints and suggestions and to Mr. E. Dittbrenner for his efforts in model construction. Miss Linda Nuss typed the report.

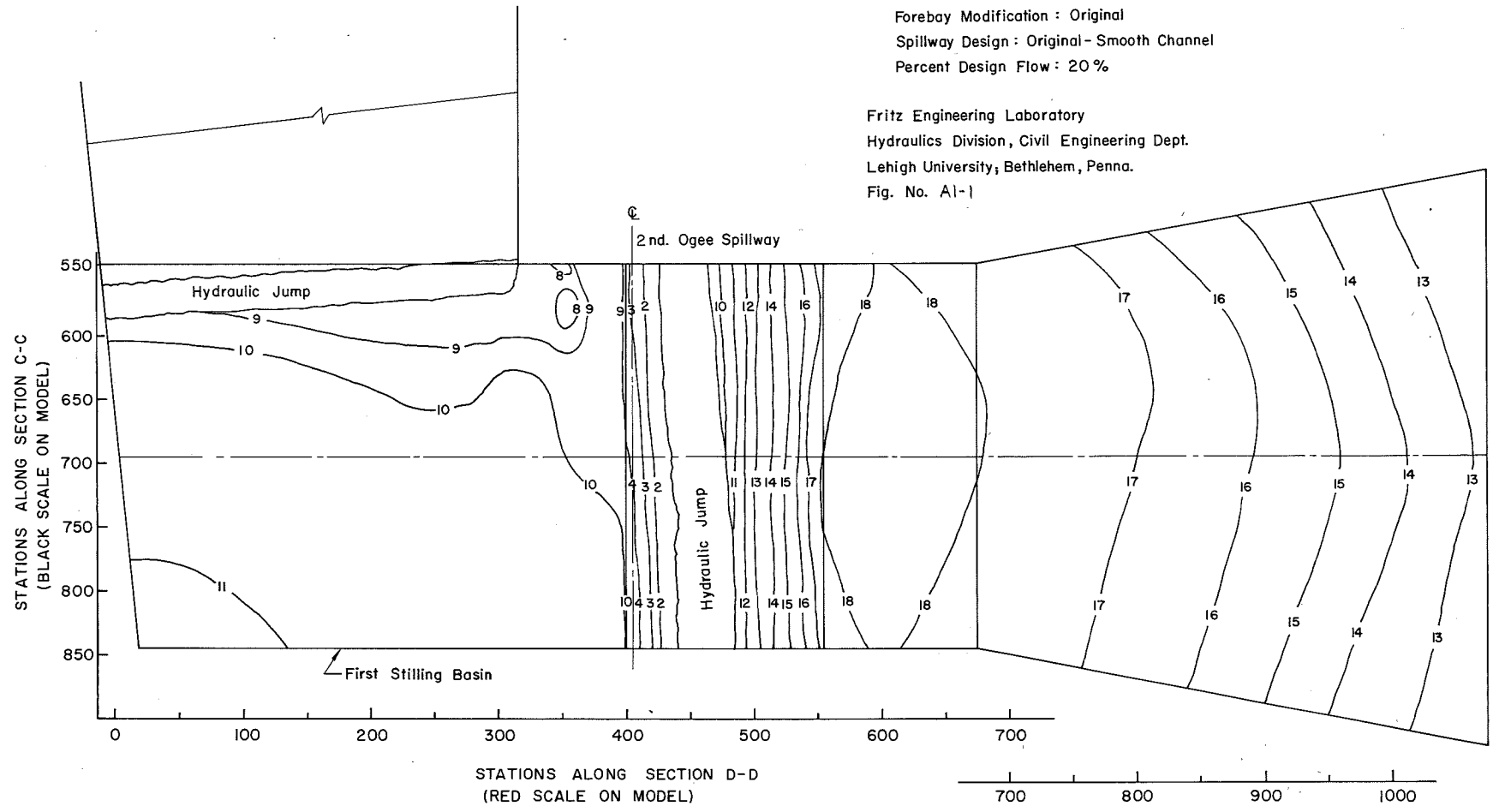
A P P E N D I C I E S

A P P E N D I X A1LOWER HALF SPILLWAY - CONTOUR MAPSList of Illustrations

<u>Figure No.</u>	<u>Title</u>
A1-1	Original Design, Smooth Channel, 20 Percent Flowrate
A1-2	Original Design, Smooth Channel, 40 Percent Flowrate
A1-3	Original Design, Smooth Channel, 60 Percent Flowrate
A1-4	Original Design, Smooth Channel, 80 Percent Flowrate
A1-5	Original Design, Smooth Channel, 100 Percent Flowrate
A1-6	Original Design, Rough Channel, 20 Percent Flowrate
A1-7	Original Design, Rough Channel, 40 Percent Flowrate
A1-8	Original Design, Rough Channel, 60 Percent Flowrate
A1-9	Original Design, Rough Channel, 80 Percent Flowrate
A1-10	Original Design, Rough Channel, 100 Percent Flowrate
A1-11	Modification Part A, Rough Channel, 20 Percent Flowrate
A1-12	Modification Part A, Rough Channel, 60 Percent Flowrate
A1-13	Modification Part A, Rough Channel, 100 Percent Flowrate
A1-14	Final Design, Rough Channel, 20 Percent Flowrate
A1-15	Final Design, Rough Channel, 60 Percent Flowrate
A1-16	Final Design, Rough Channel, 100 Percent Flowrate

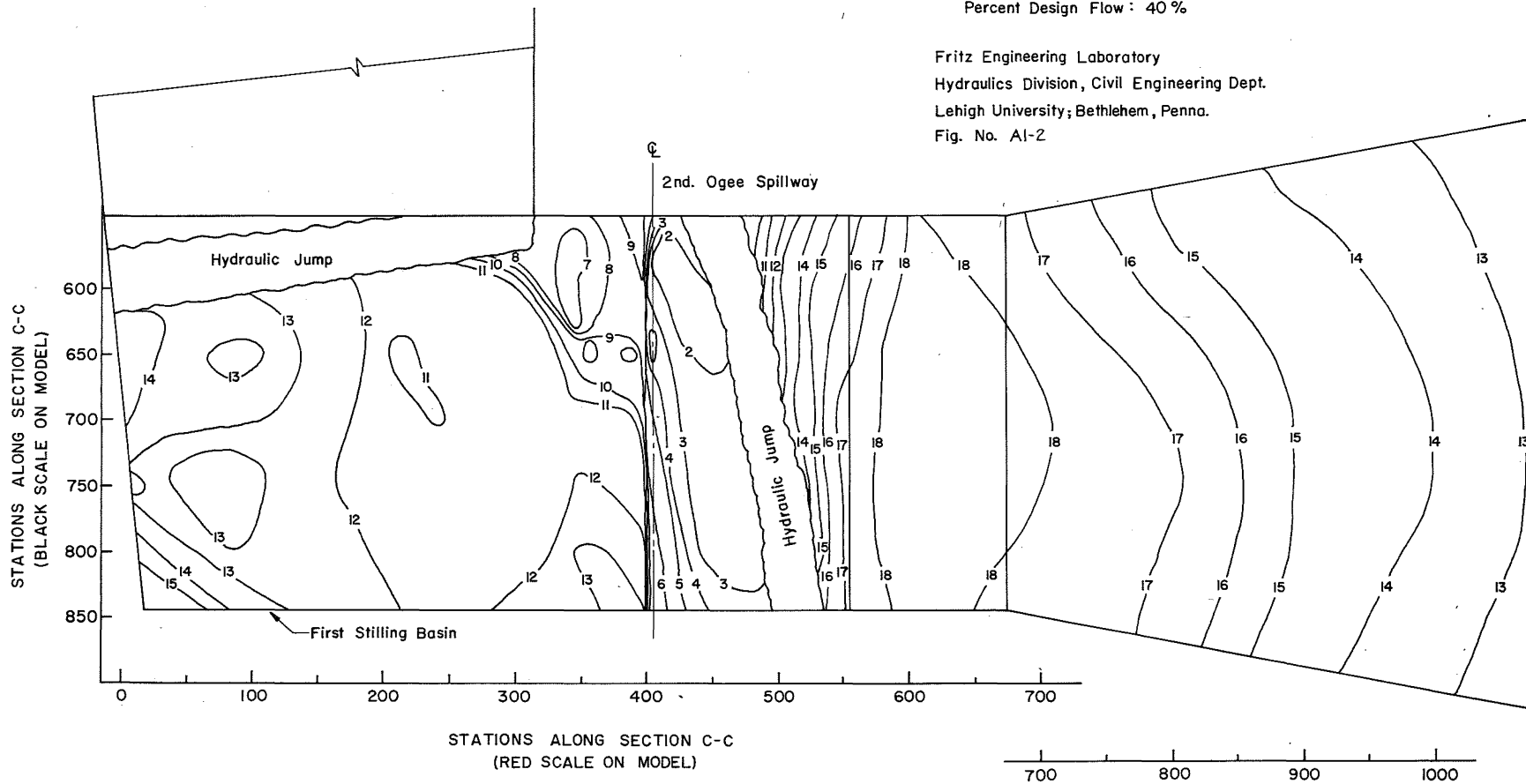
Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS
 Forebay Modification : Original
 Spillway Design : Original - Smooth Channel
 Percent Design Flow : 20 %

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 Hydraulics Division, Civil Engineering Dept.
 Lehigh University, Bethlehem, Penna.
 Fig. No. A1-1



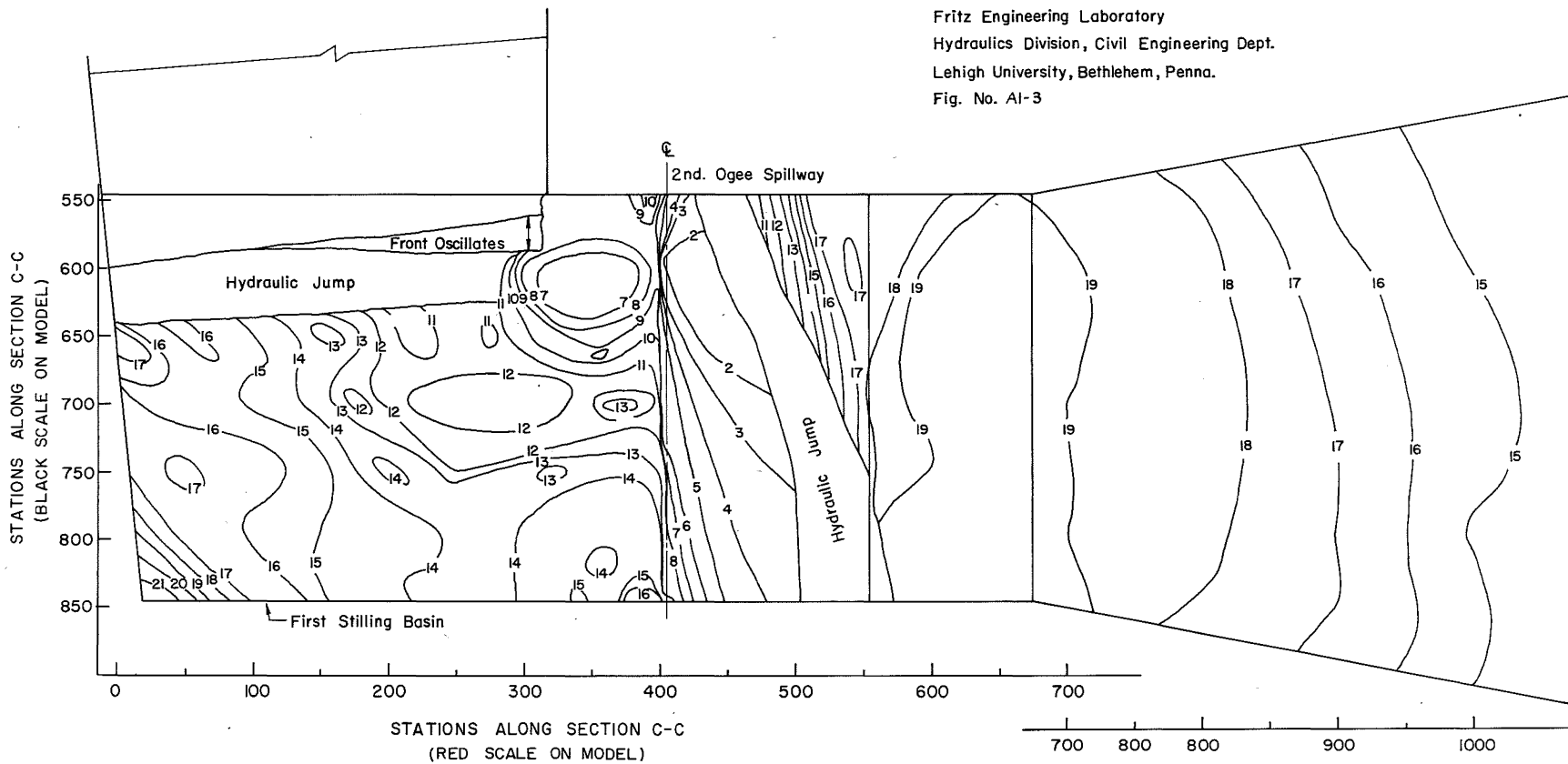
Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS
 Forebay Modification : Original
 Spillway Design : Original - Smooth Channel
 Percent Design Flow : 40 %

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 Fig. No. A1-2



Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS
 Forebay Modification : Original
 Spillway Design : Original - Smooth Channel
 Percent Design Flow : 60 %

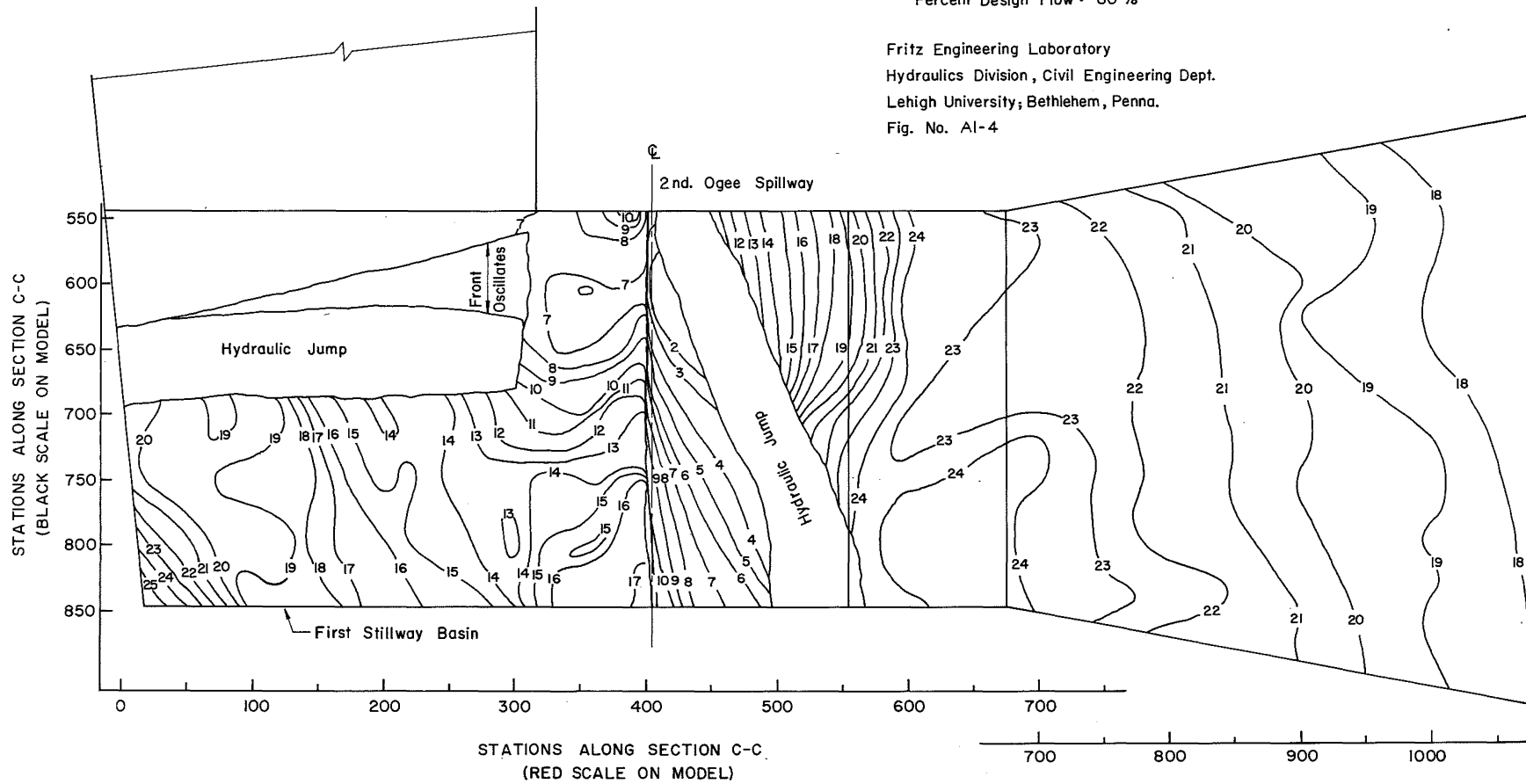
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 Fig. No. AI-3



Project 1050-326
NOCKAMIXON SPILLWAY MODEL
PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS

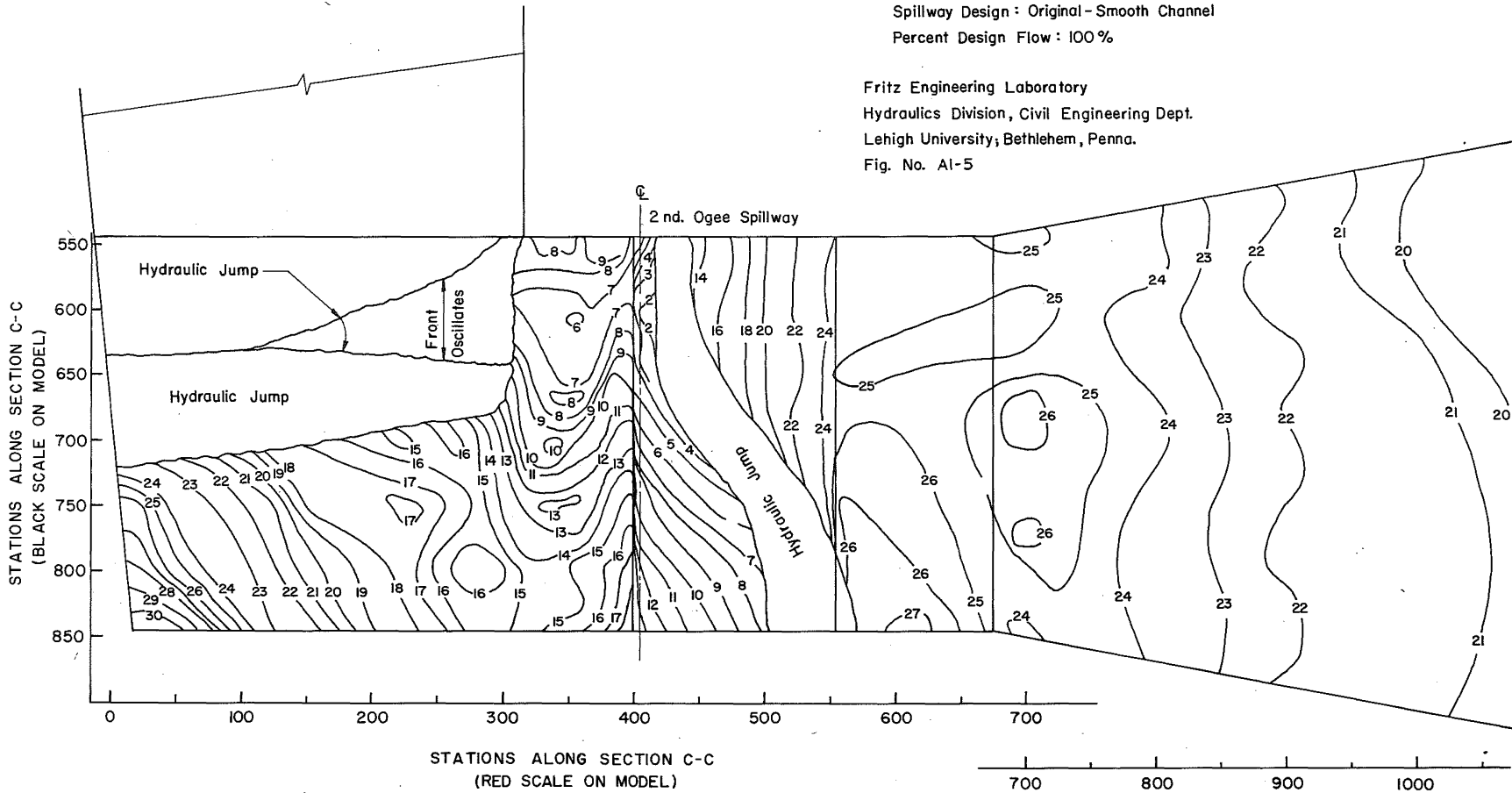
Forebay Modification : Original
Spillway Design : Original-Smooth Channel
Percent Design Flow : 80 %

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Fig. No. AI-4



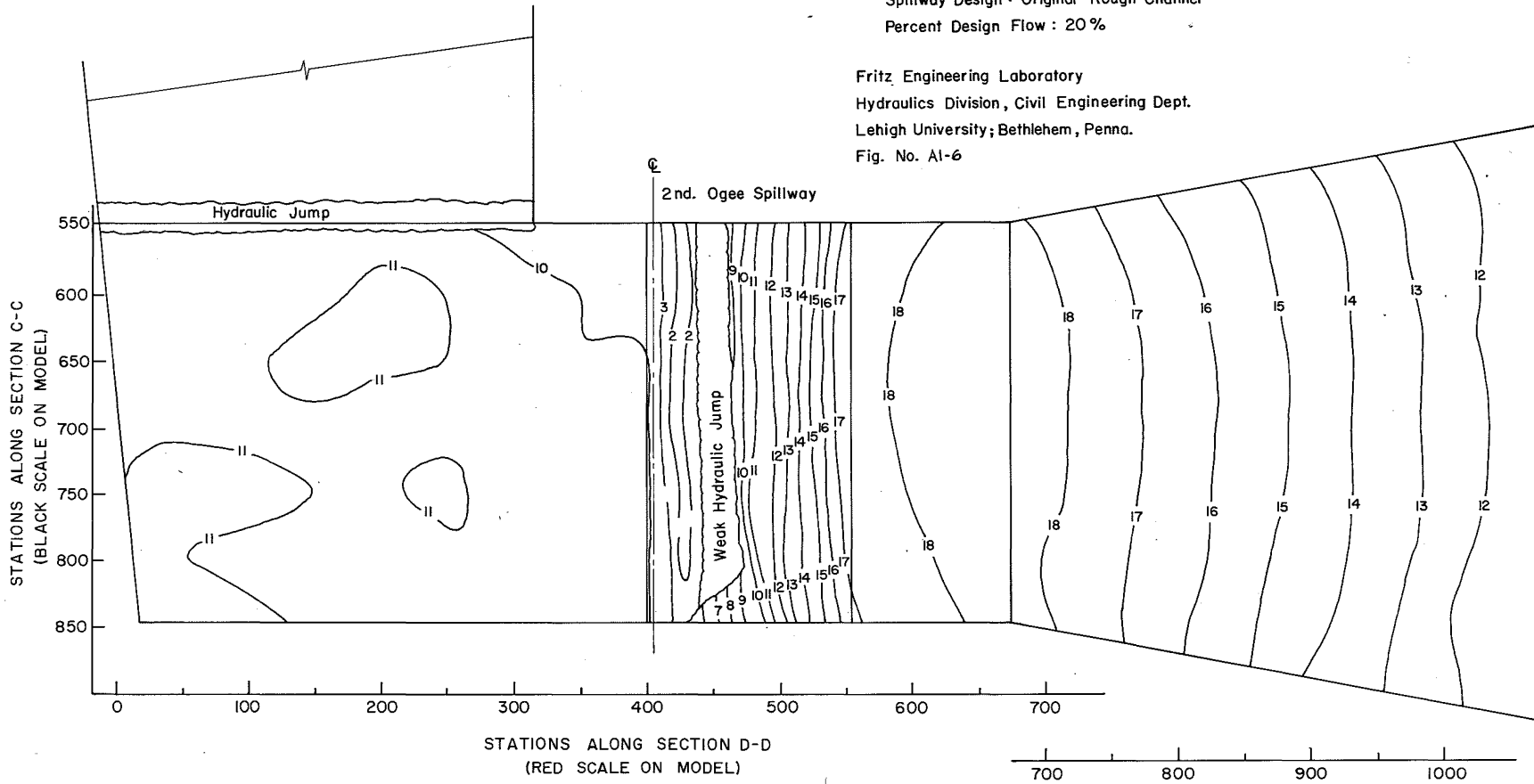
Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS
 Forebay Modification : Original
 Spillway Design : Original - Smooth Channel
 Percent Design Flow : 100 %

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 Fig. No. A1-5



Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS
 Forebay Modification : Original
 Spillway Design : Original - Rough Channel
 Percent Design Flow : 20 %

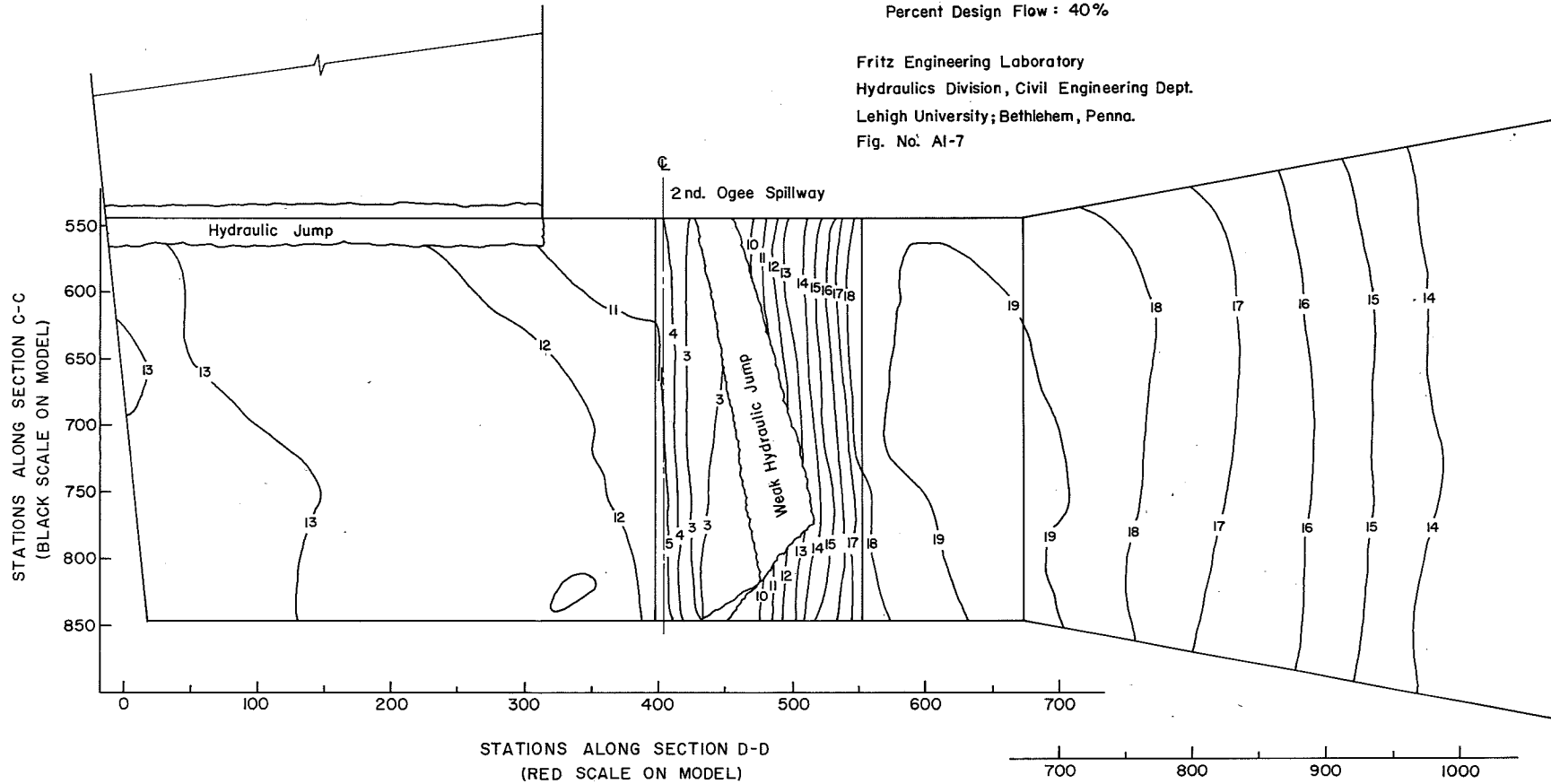
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 Fig. No. A1-6



Project 1050-326
NOCKAMIXON SPILLWAY MODEL
PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS

Forebay Modification : Original
Spillway Design : Original - Rough Channel
Percent Design Flow : 40%

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Fig. No. A1-7



Project IO50-326

NOCKAMIXON SPILLWAY MODEL

PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS

Forebay Modification : Original

Spillway Design : Original -Rough Channel

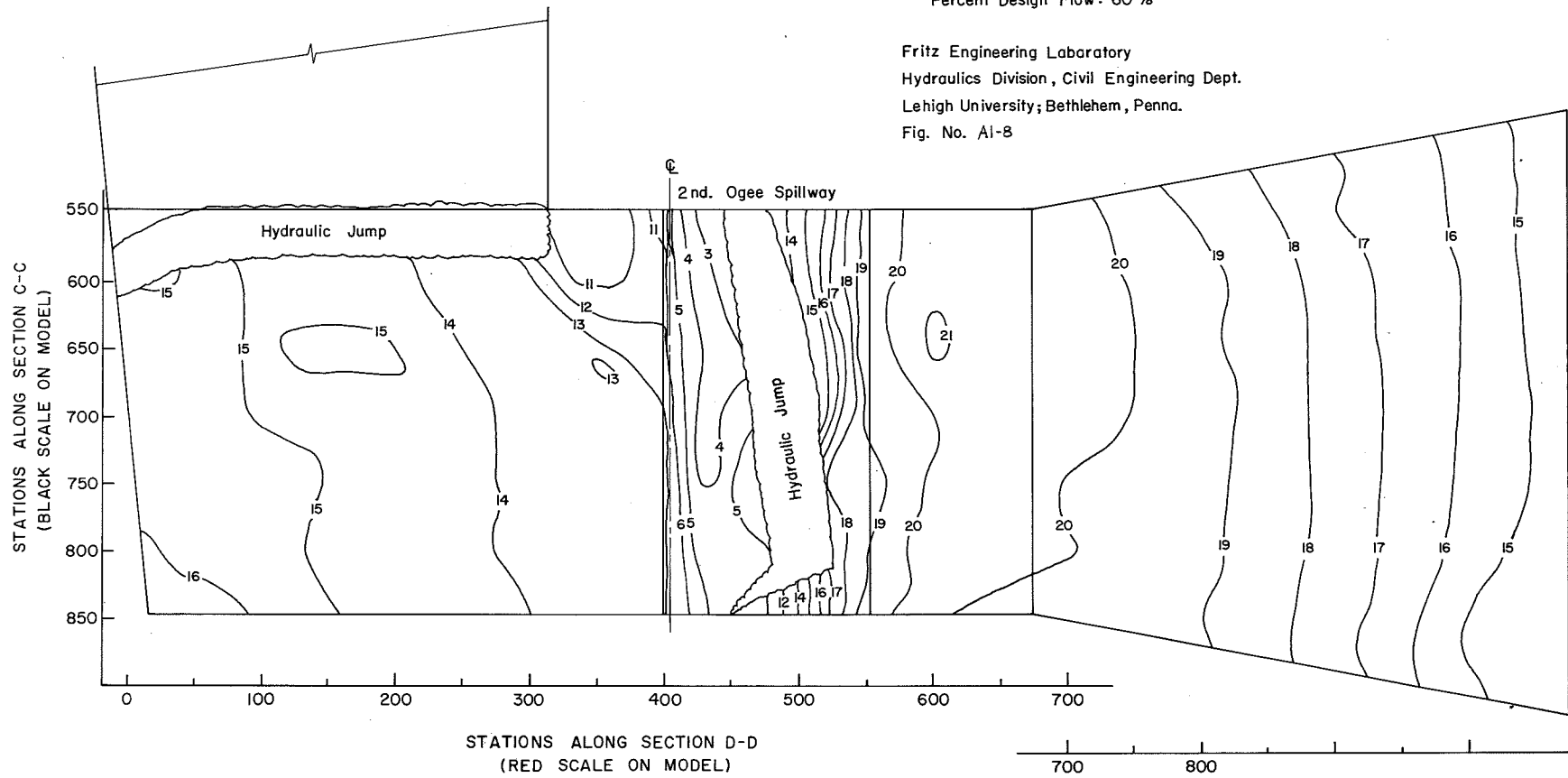
Percent Design Flow : 60 %

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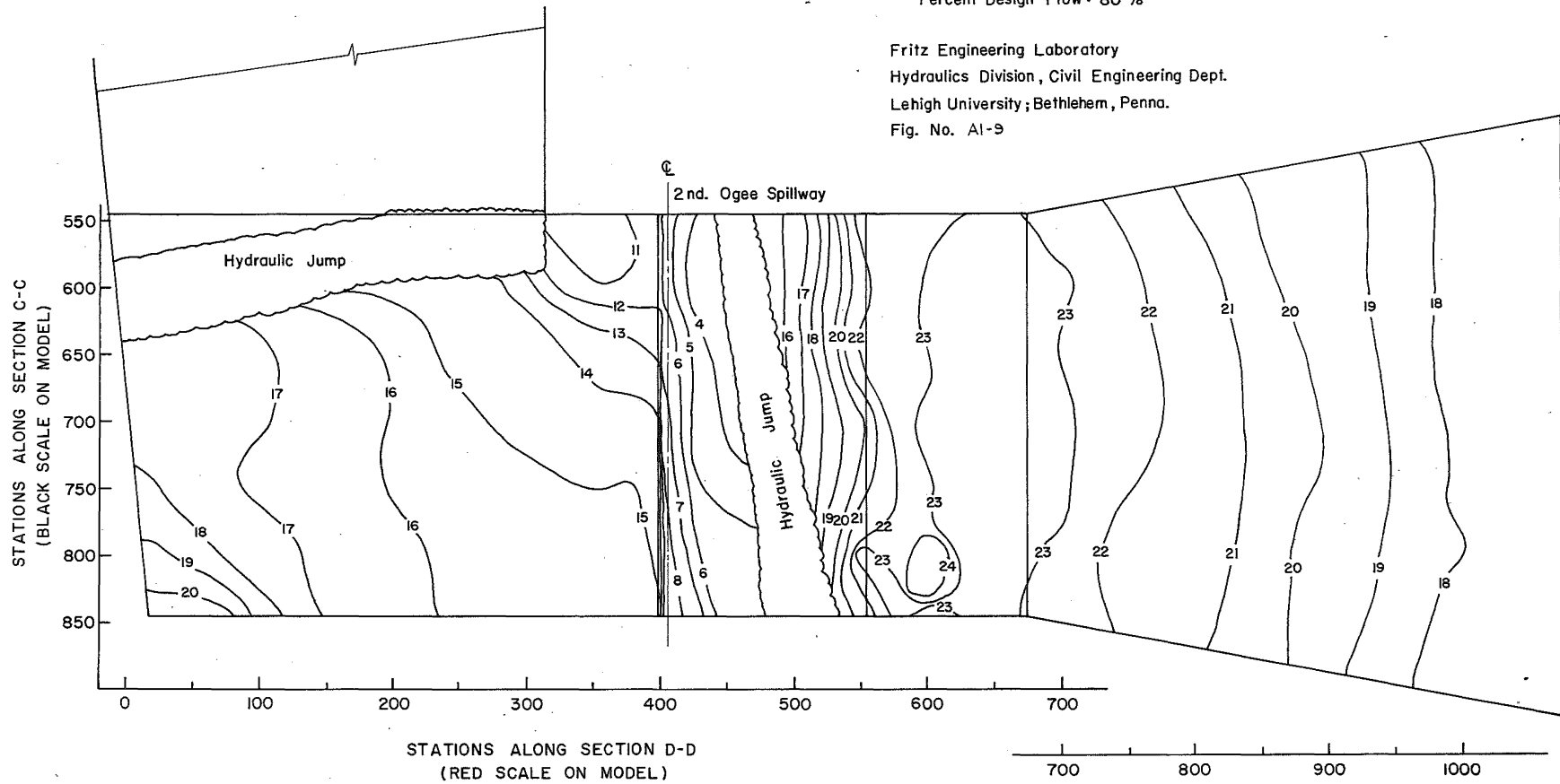
Lehigh University, Bethlehem, Penna.

Fig. No. AI-8



Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS
 Forebay Modification : Original
 Spillway Design : Original Design - Rough Channel
 Percent Design Flow : 80 %

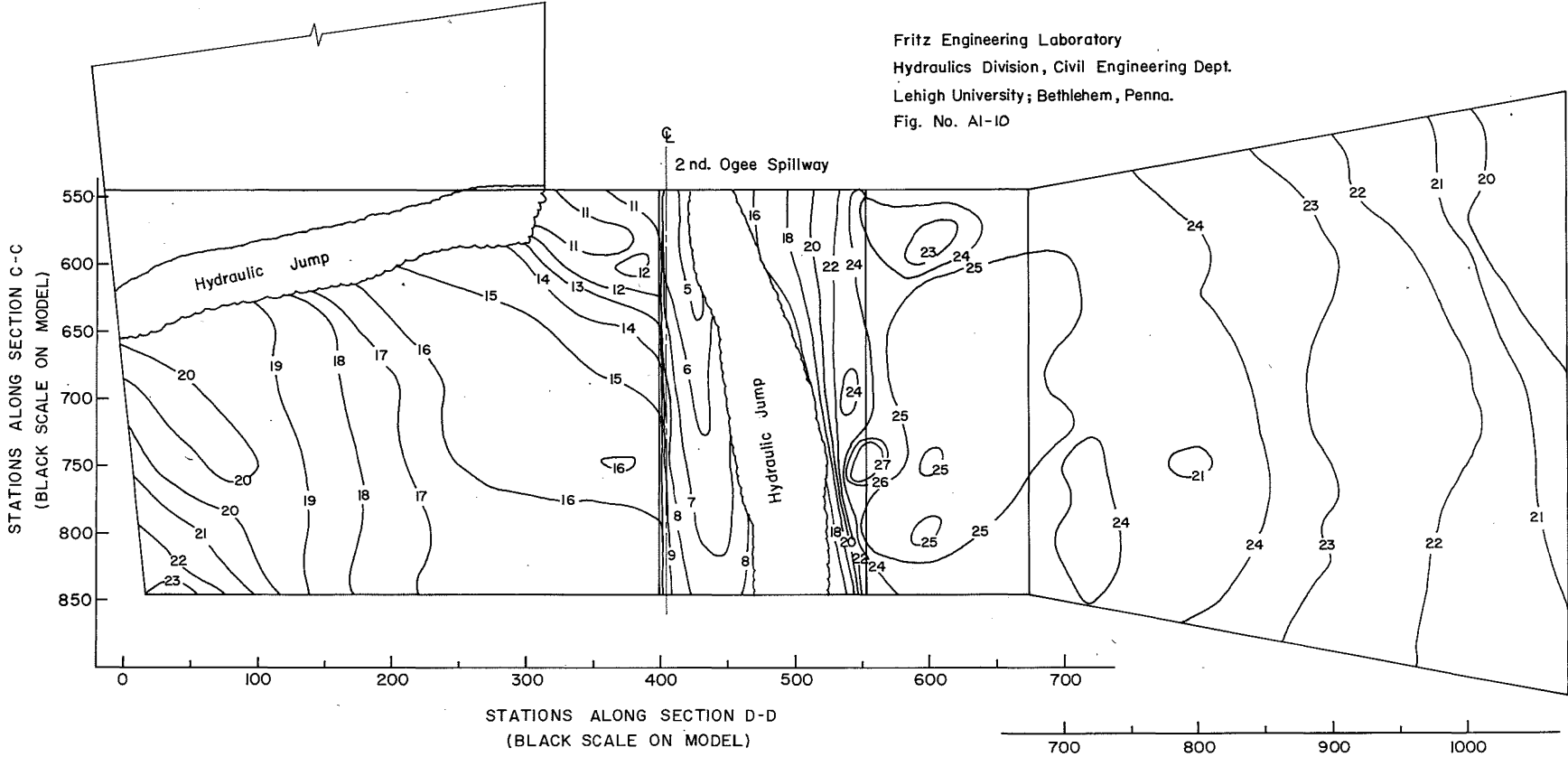
Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University, Bethlehem, Penna.
 Fig. No. A1-9



Project IO50-326
NOCKAMIXON SPILLWAY MODEL
PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS

Forebay Modification : Original Design
Spillway Design : Original Design - Rough Channel
Percent Design Flow : 100 %

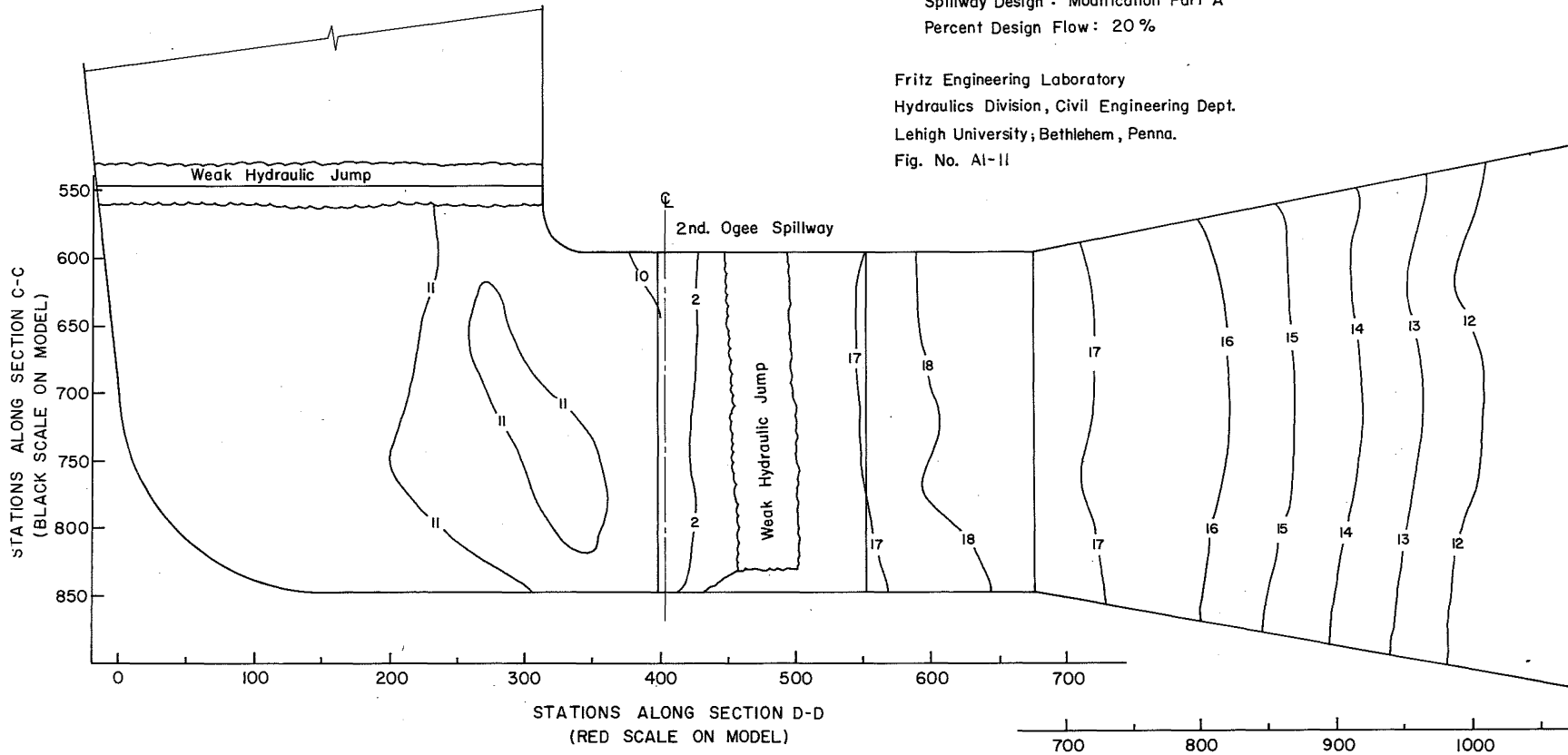
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Fig. No. A1-10



Project 1050-326
NOCKAMIXON SPILLWAY MODEL
PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS

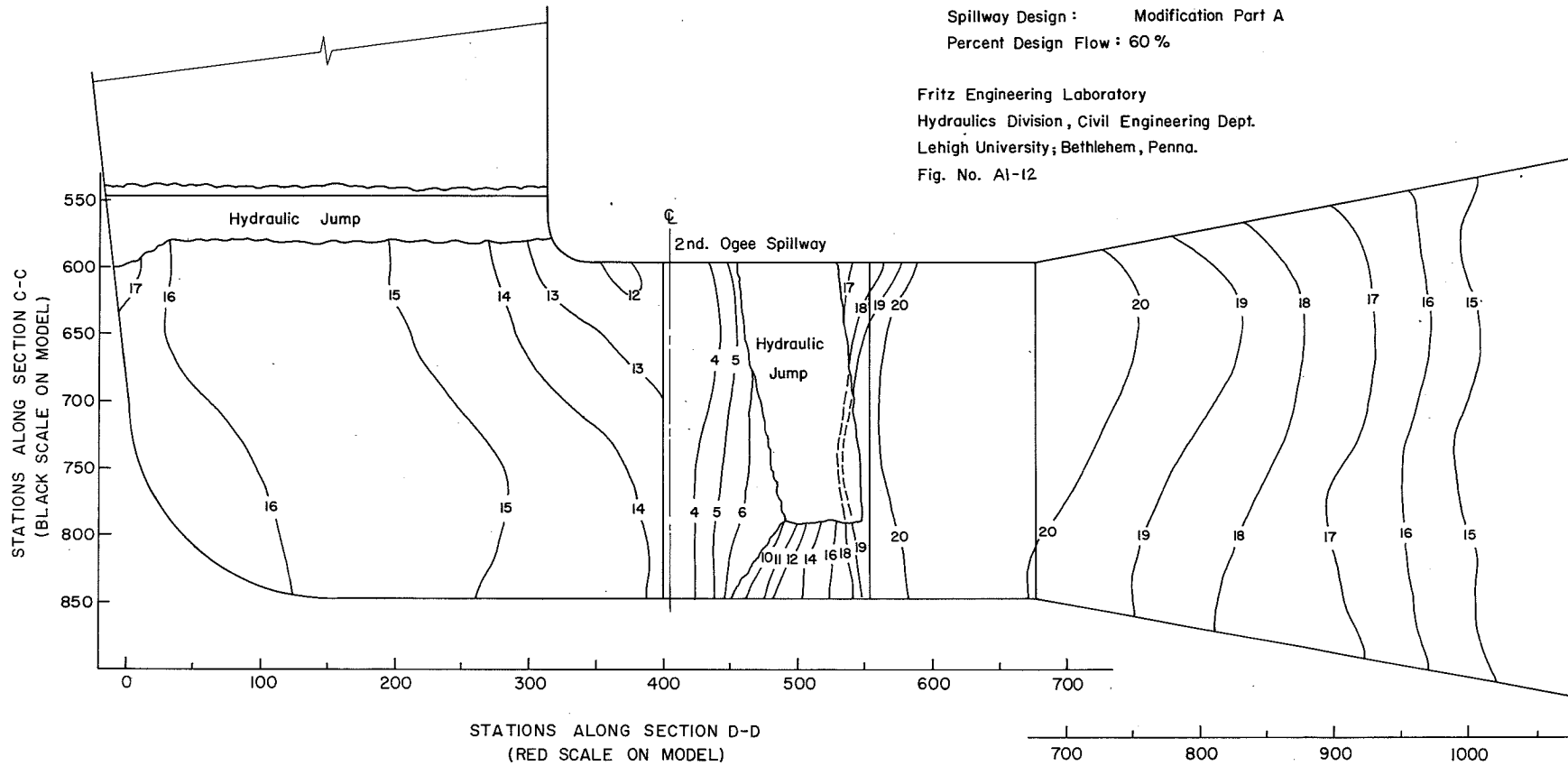
Forebay Modification : No. 2
Spillway Design : Modification Part A
Percent Design Flow : 20 %

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Fig. No. A1-11



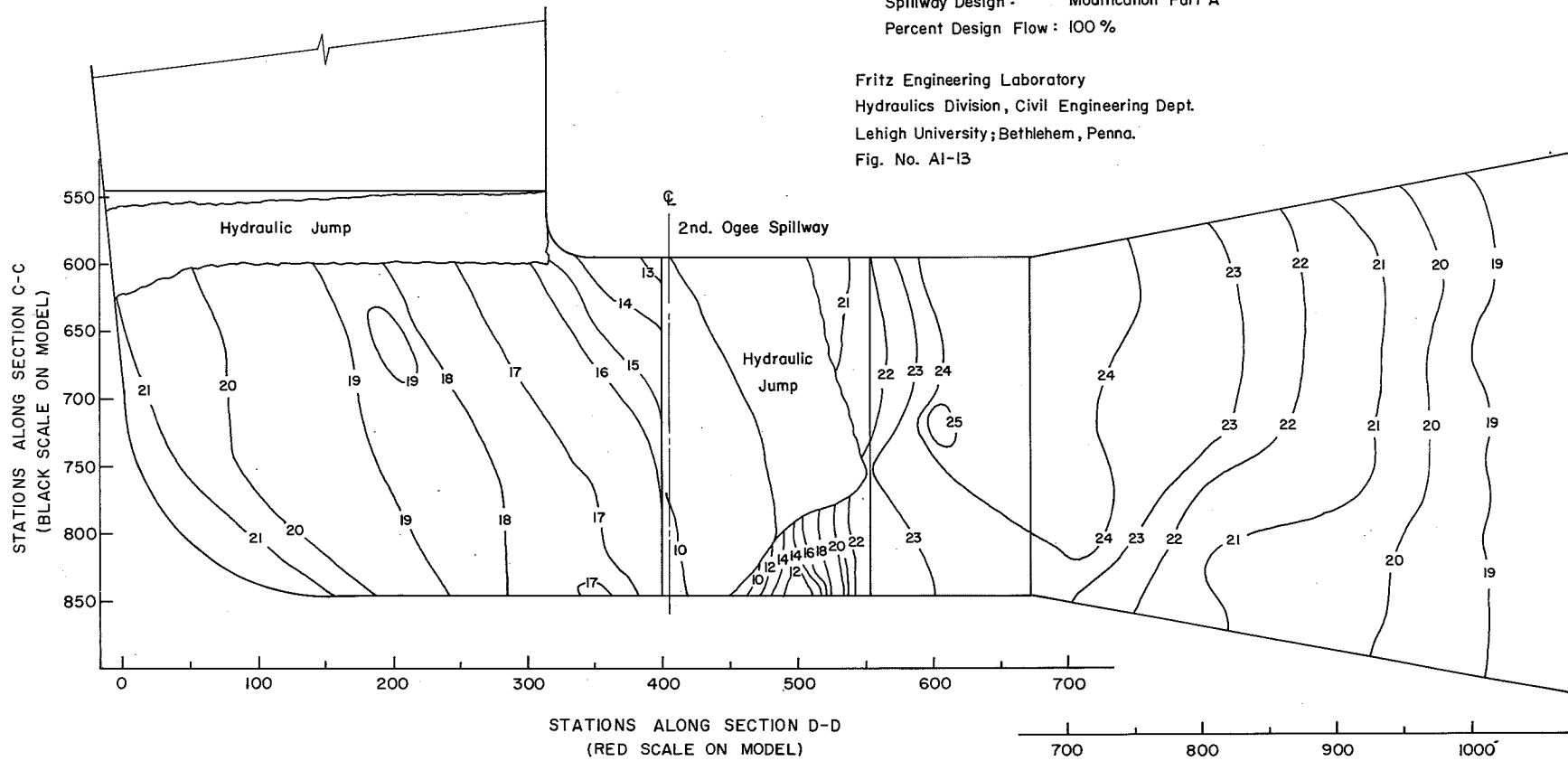
Project 1050-326
NOCKAMIXON SPILLWAY MODEL
PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS
Forebay Modification : Final No. 2
Spillway Design : Modification Part A
Percent Design Flow : 60 %

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Fig. No. A1-12



Project I050-326
 NOCKAMIXON SPILLWAY MODEL
 PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS
 Forebay Modification : Final No. 2
 Spillway Design : Modification Part A
 Percent Design Flow : 100 %

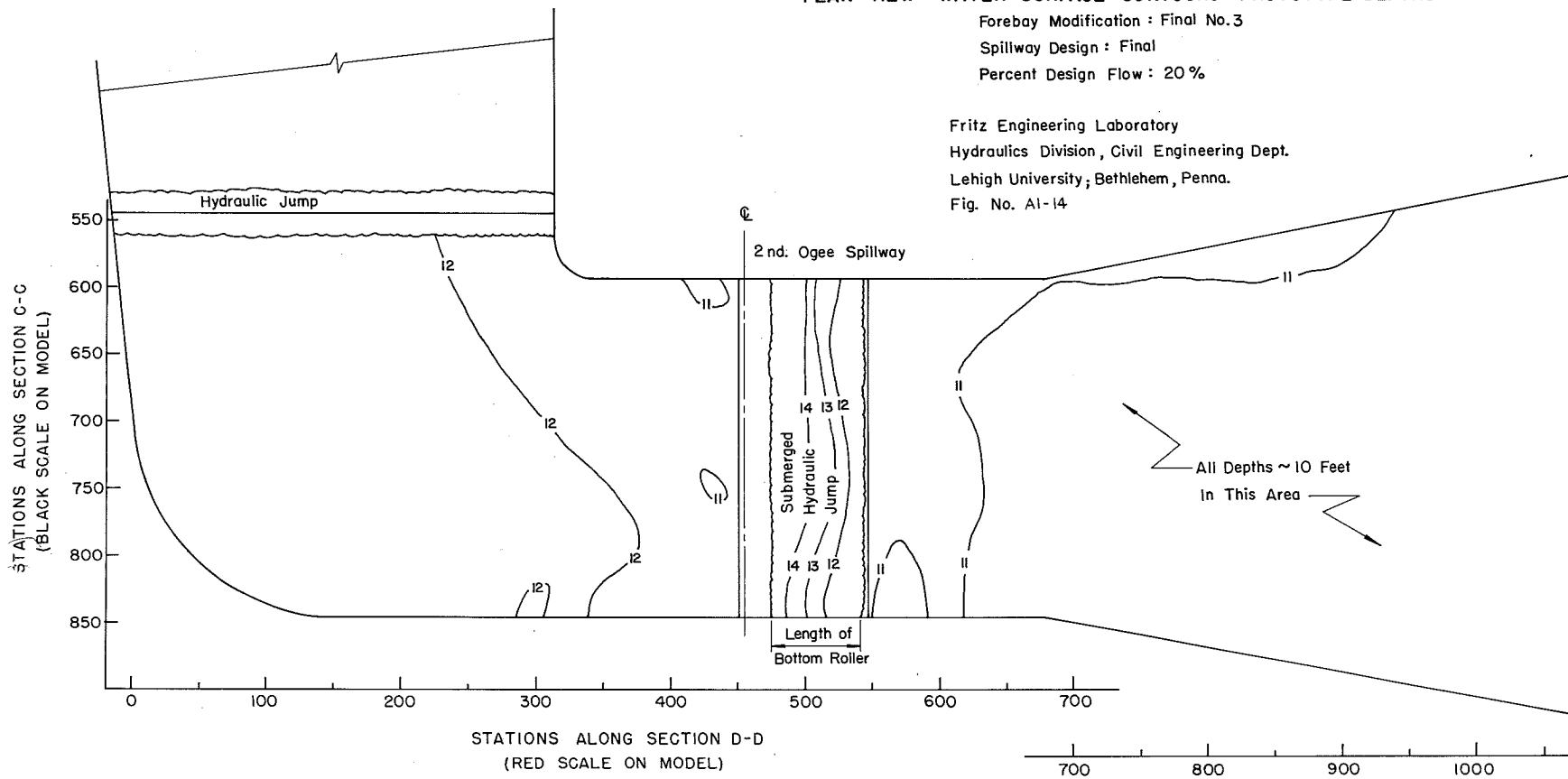
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 Fig. No. AI-13



Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS

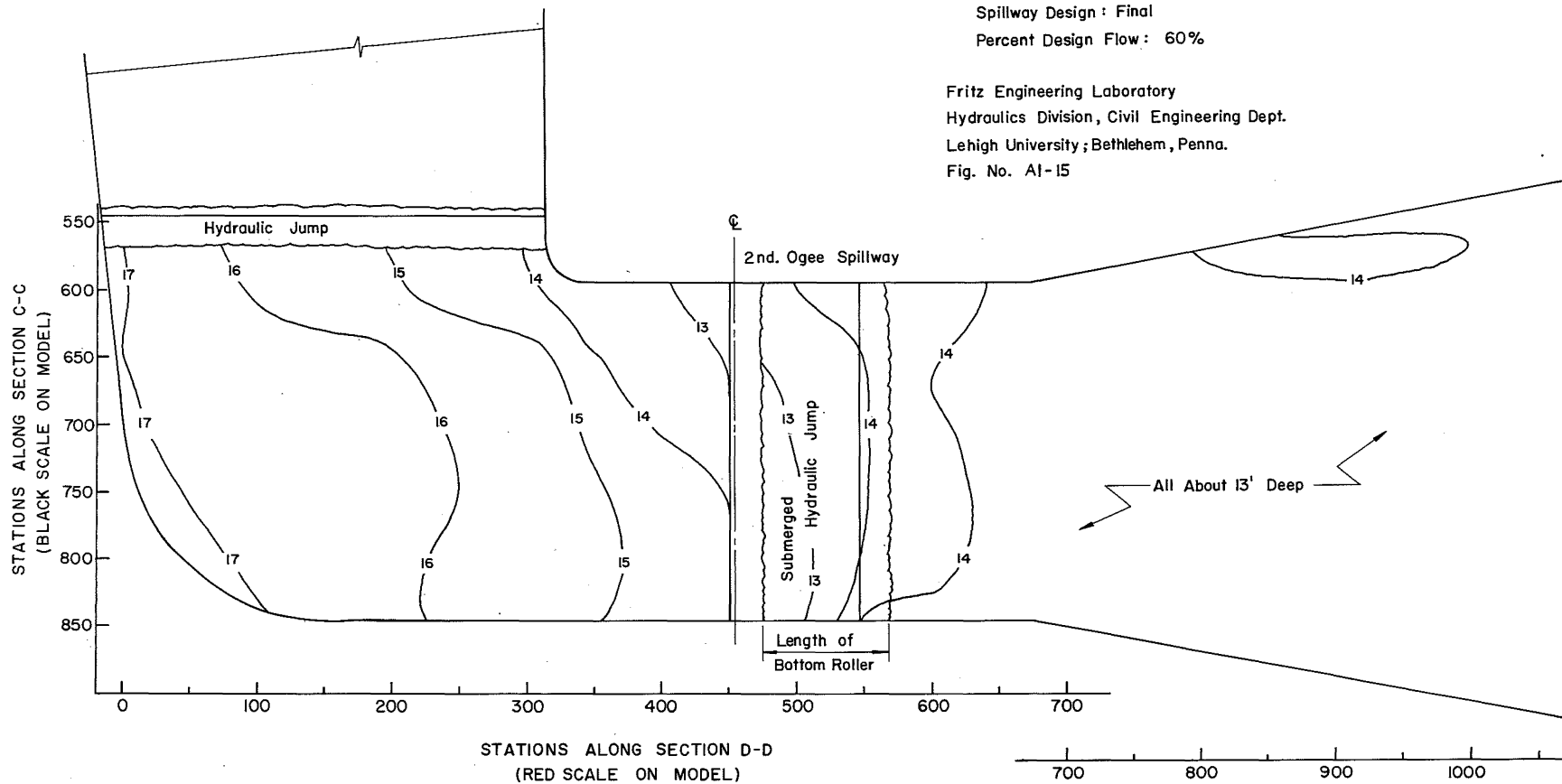
Forebay Modification : Final No.3
 Spillway Design : Final
 Percent Design Flow : 20 %

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 Fig. No. A1-14



Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS
 Forebay Modification : Final No. 3
 Spillway Design : Final
 Percent Design Flow : 60%

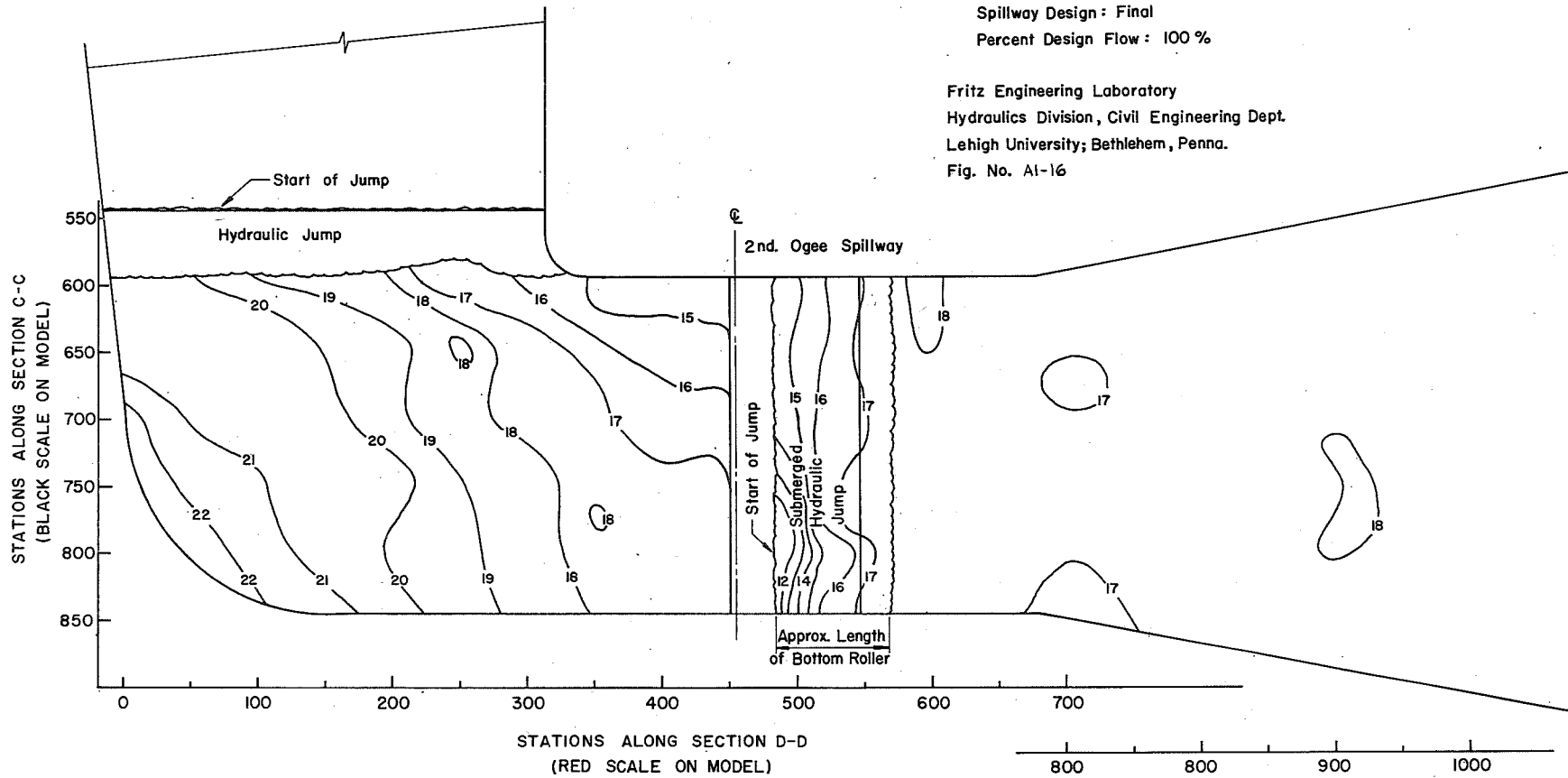
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 Fig. No. A1-15



Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 PLAN VIEW - WATER SURFACE CONTOURS - PROTOTYPE DEPTHS

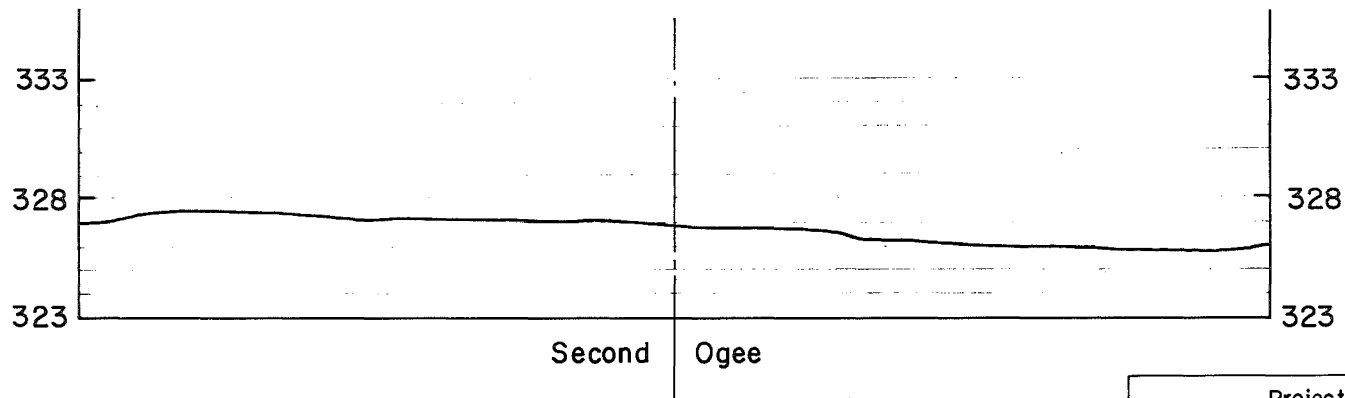
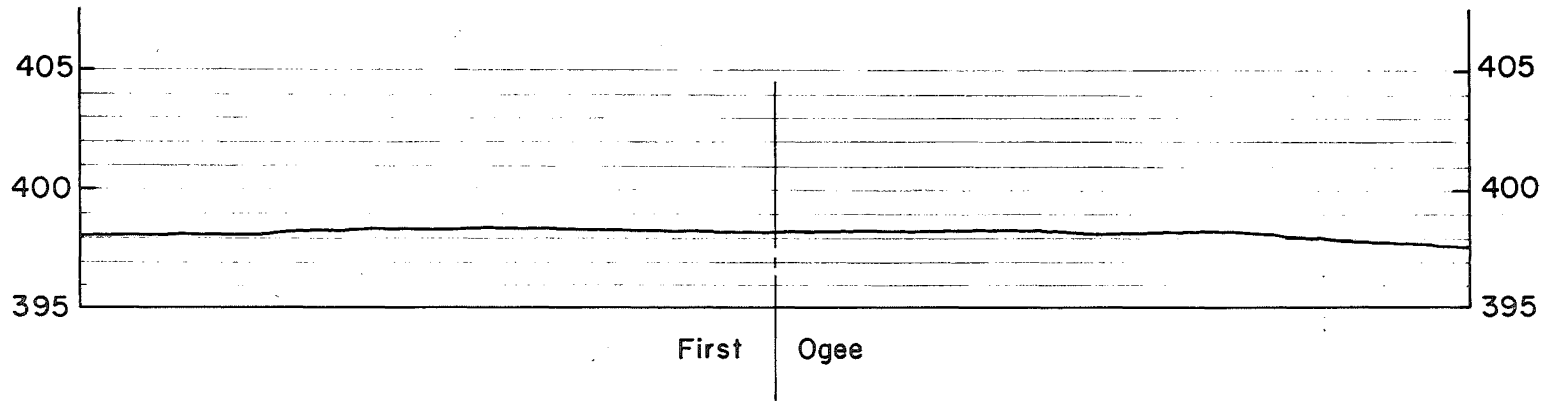
Forebay Modification : Final No. 3
 Spillway Design : Final
 Percent Design Flow : 100 %

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 Fig. No. AI-16



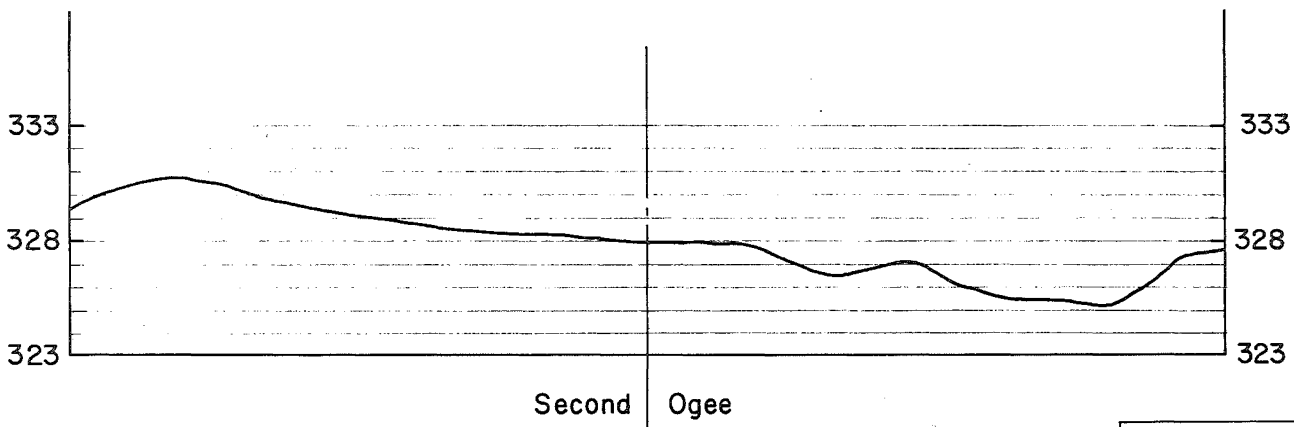
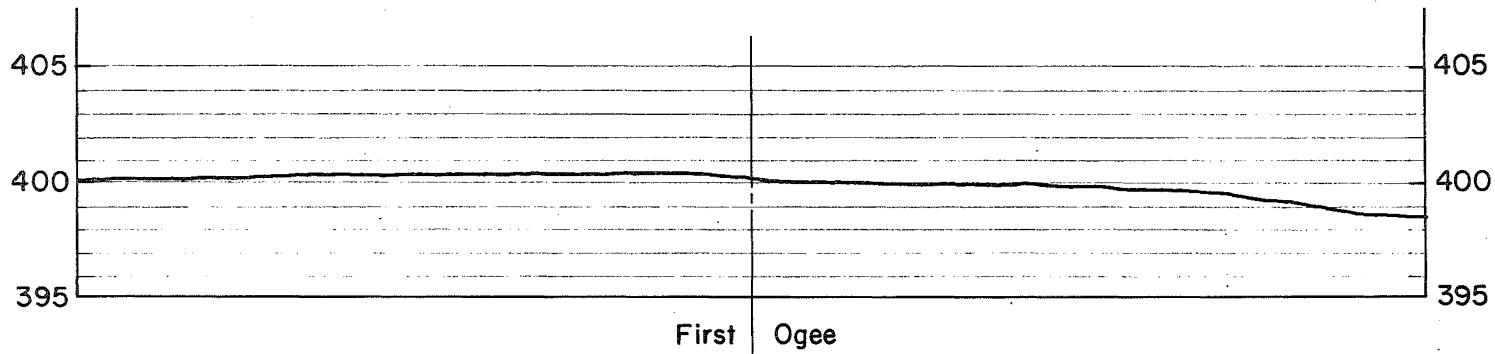
A P P E N D I X A2WEIR CROSS SECTIONSList of Illustrations

<u>Figure No.</u>	<u>Title</u>
A2-1	Original Design, Smooth Channel, 20 Percent Flowrate
A2-2	Original Design, Smooth Channel, 40 Percent Flowrate
A2-3	Original Design, Smooth Channel, 60 Percent Flowrate
A2-4	Original Design, Smooth Channel, 80 Percent Flowrate
A2-5	Original Design, Smooth Channel, 100 Percent Flowrate
A2-6	Original Design, Rough Channel, 20 Percent Flowrate
A2-7	Original Design, Rough Channel, 40 Percent Flowrate
A2-8	Original Design, Rough Channel, 60 Percent Flowrate
A2-9	Original Design, Rough Channel, 80 Percent Flowrate
A2-10	Original Design, Rough Channel, 100 Percent Flowrate
A2-11	Forebay Modification No.I, Rough Channel, 20 Percent Flowrate
A2-12	Forebay Modification No.I, Rough Channel, 40 Percent Flowrate
A2-13	Forebay Modification No.I, Rough Channel, 60 Percent Flowrate
A2-14	Forebay Modification No.I, Rough Channel, 80 Percent Flowrate
A2-15	Forebay Modification No.I, Rough Channel, 100 Percent Flowrate
A2-16	Forebay Modification No.II, Rough Channel, 20 Percent Flowrate
A2-17	Forebay Modification No.II, Rough Channel, 40 Percent Flowrate
A2-18	Forebay Modification No.II, Rough Channel, 60 Percent Flowrate
A2-19	Forebay Modification No.III, Rough Channel, 20 Percent Flowrate
A2-20	Forebay Modification No.III, Rough Channel, 60 Percent Flowrate
A2-21	Forebay Modification No.III, Rough Channel, 100 Percent Flowrate



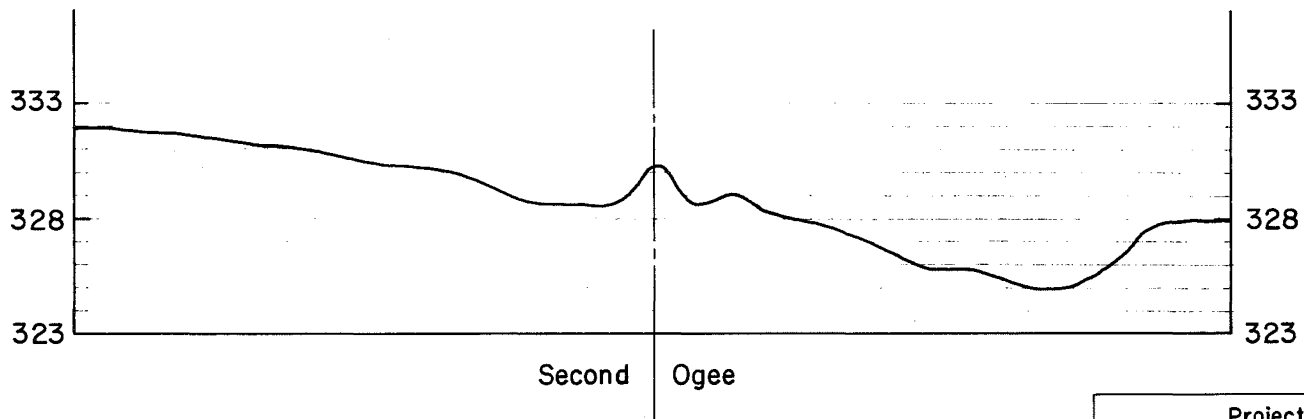
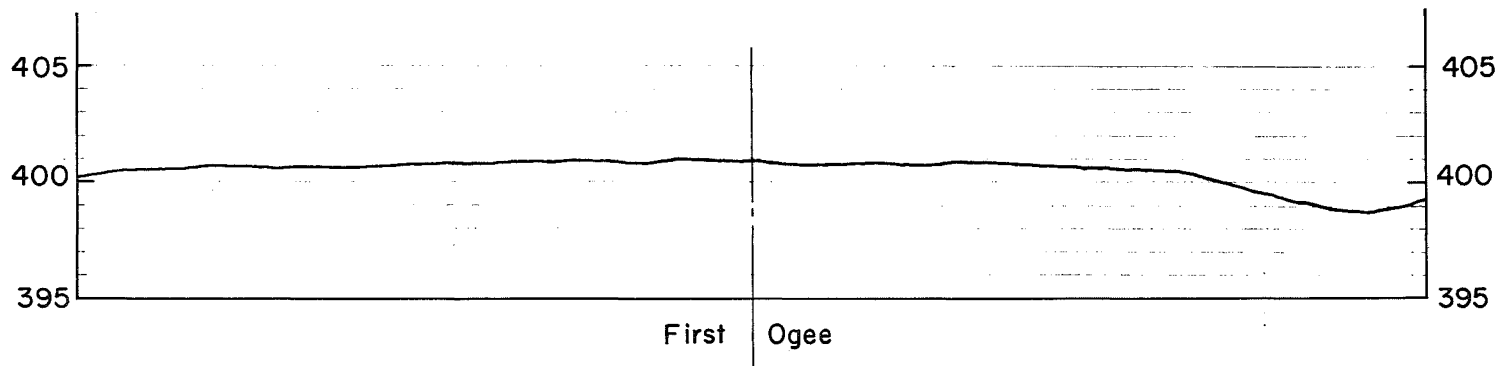
Both Views Looking Upstream

Project I050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Original
 Spillway Design - Original Unmodified
 Design Flow - 20% No Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-1



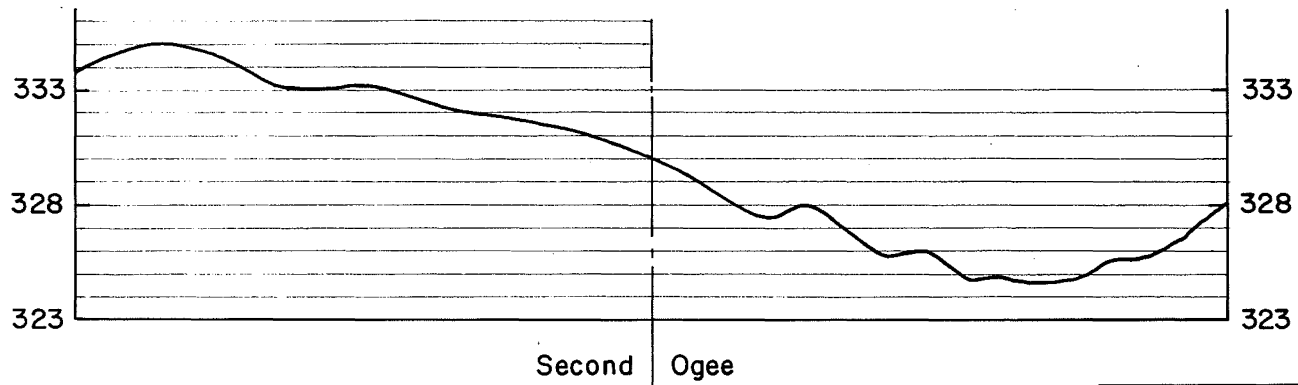
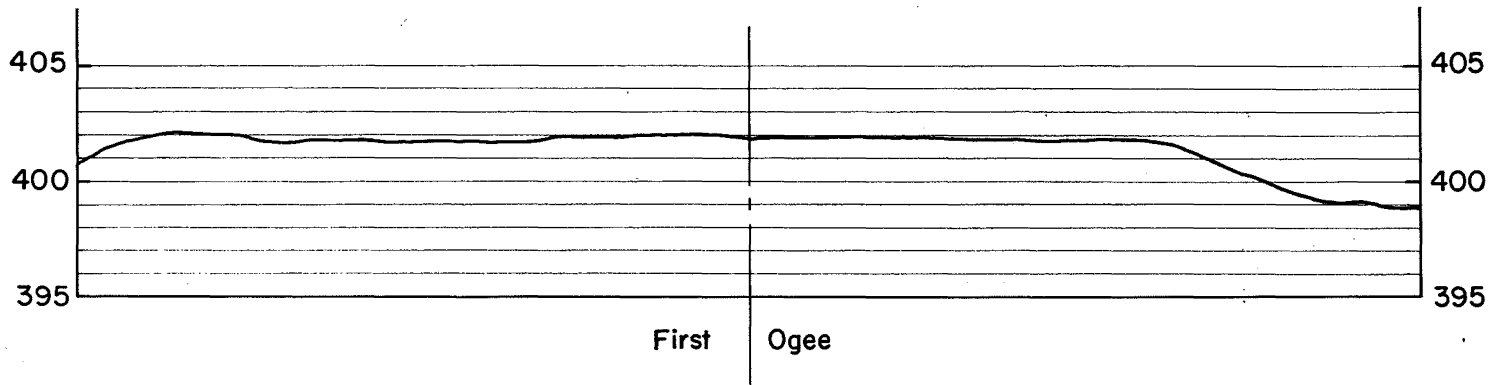
Both Views Looking Upstream

Project I050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Unmodified
 Spillway Design - Unmodified
 Design Flow - 40% - No Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-2



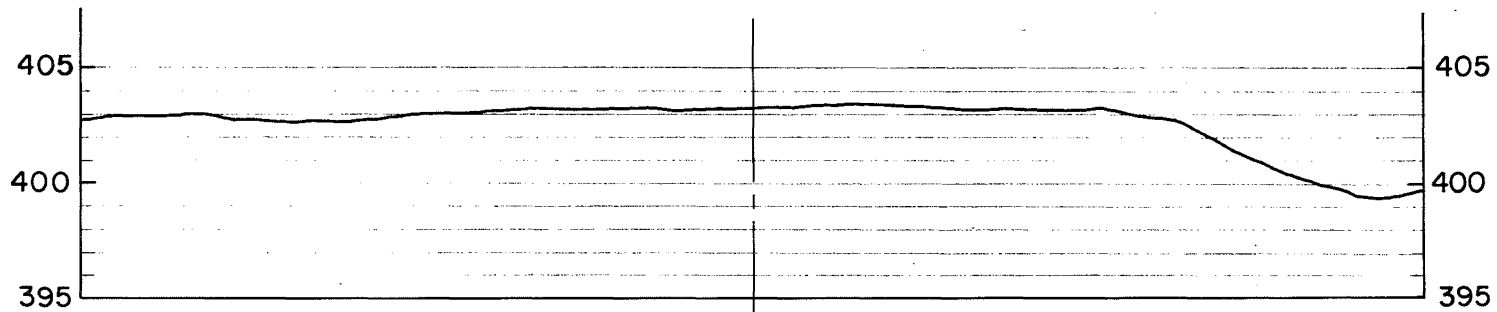
Both Views Looking Upstream

Project I050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Original
 Spillway Design - Unmodified
 Design Flow - 60% - No Roughness
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 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-3

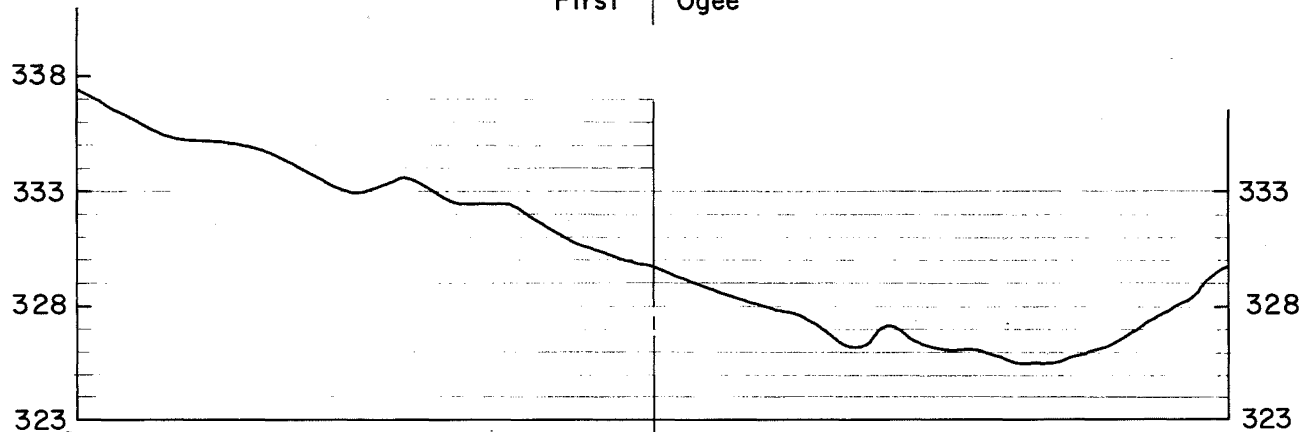


Both Views Looking Upstream

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Original
 Spillway Design - Unmodified
 Design Flow - 80% - No Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-4



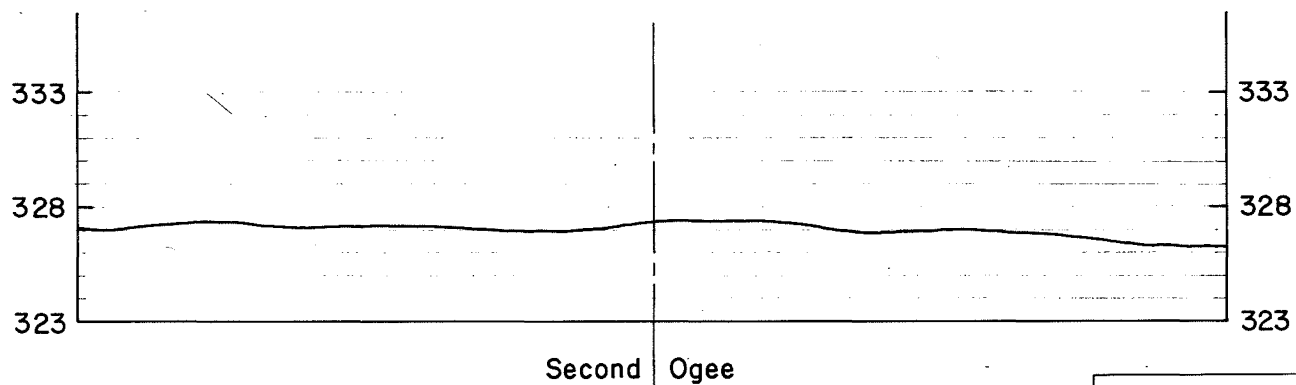
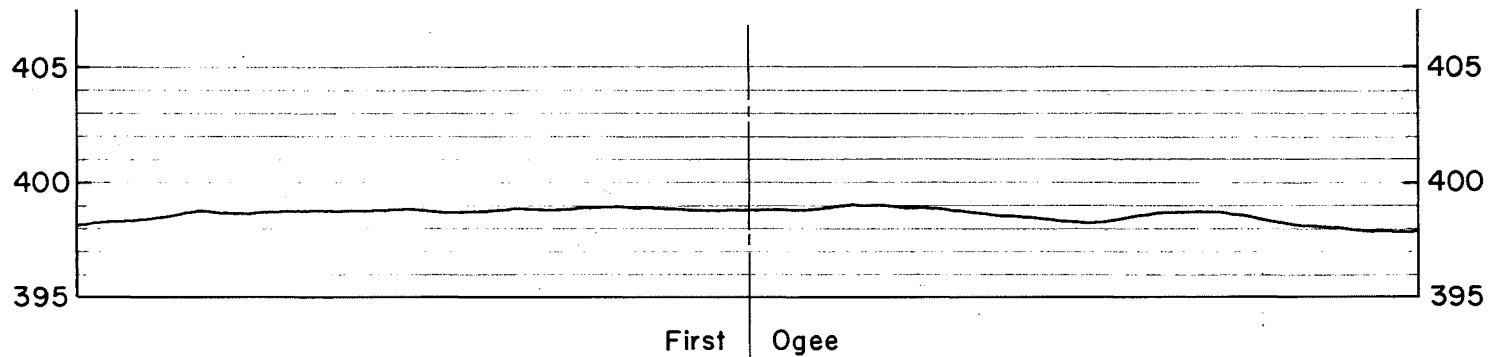
First Ogee



Second Ogee

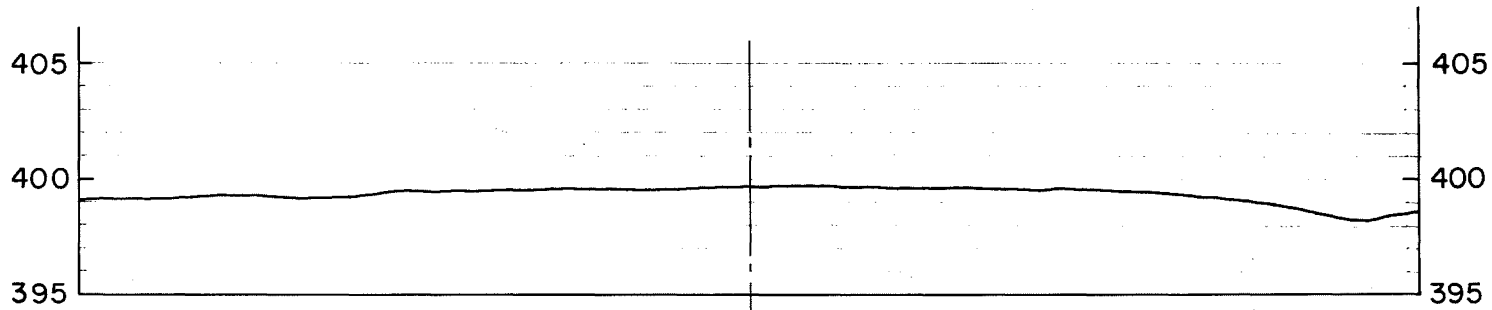
Both Views Looking Upstream

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Original
 Spillway Design - Unmodified
 Design Flow - 100% - No Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-5

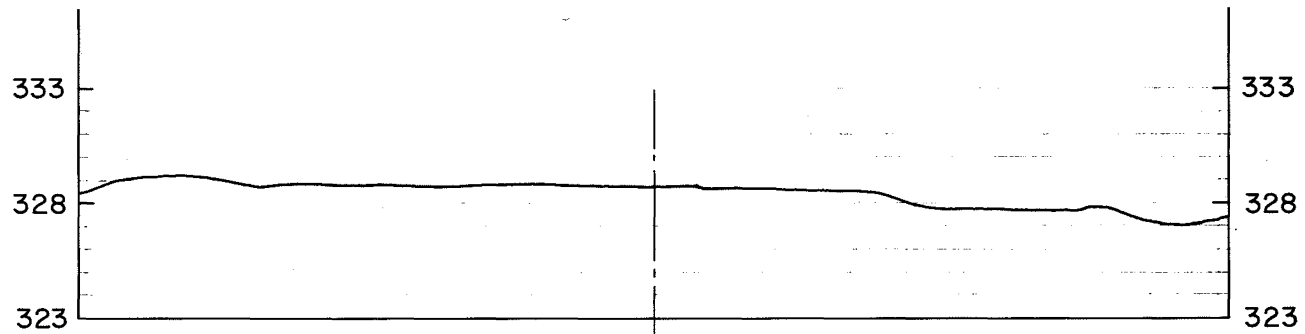


Both Views Looking Upstream

Project IO50-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Original
 Spillway Design - Unmodified
 Design Flow - 20% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-6



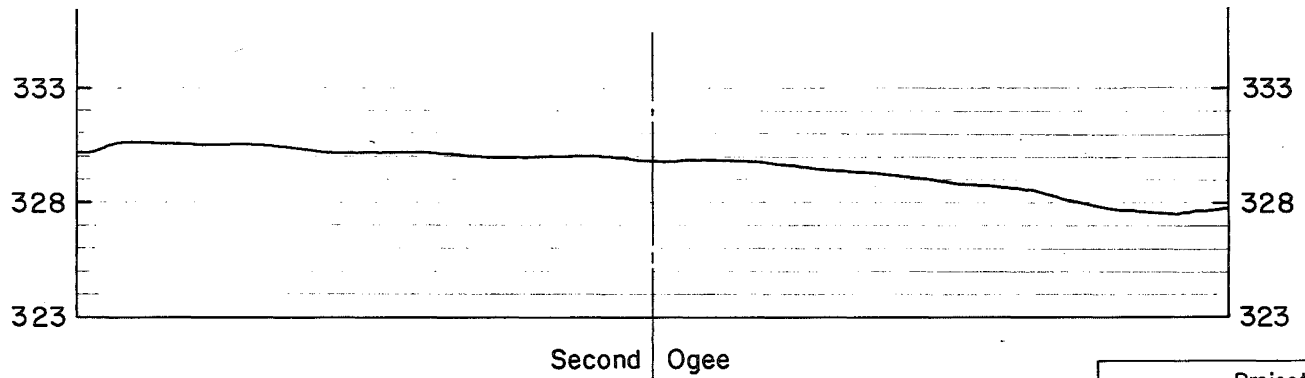
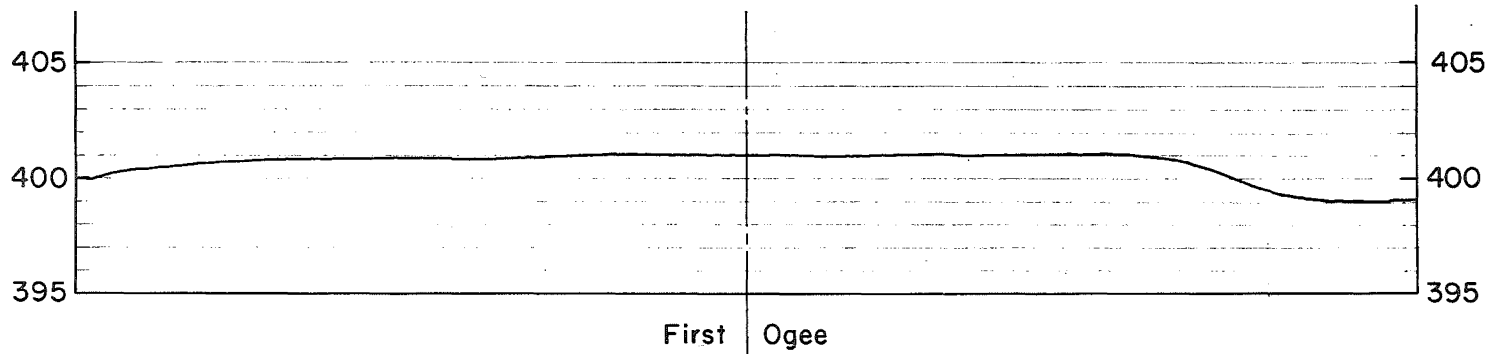
First Ogee



Second Ogee

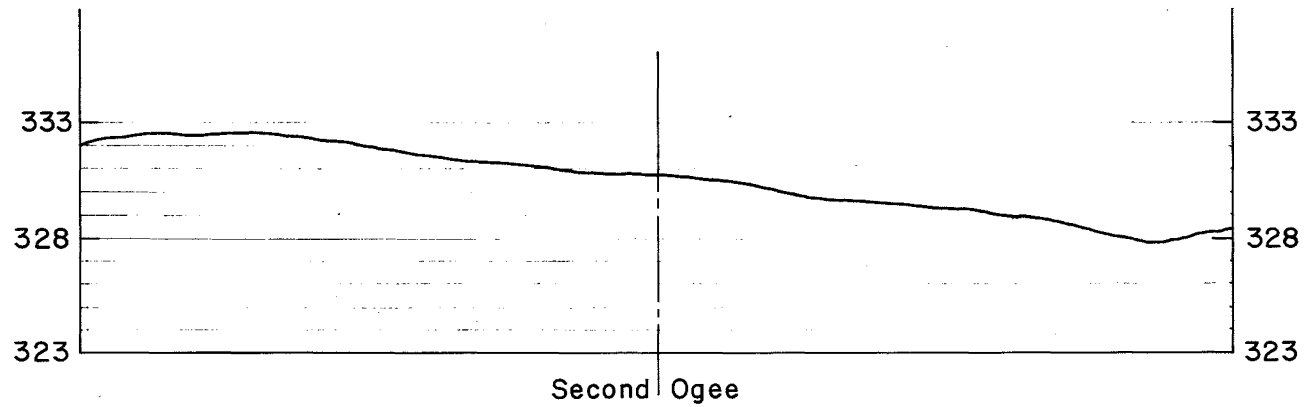
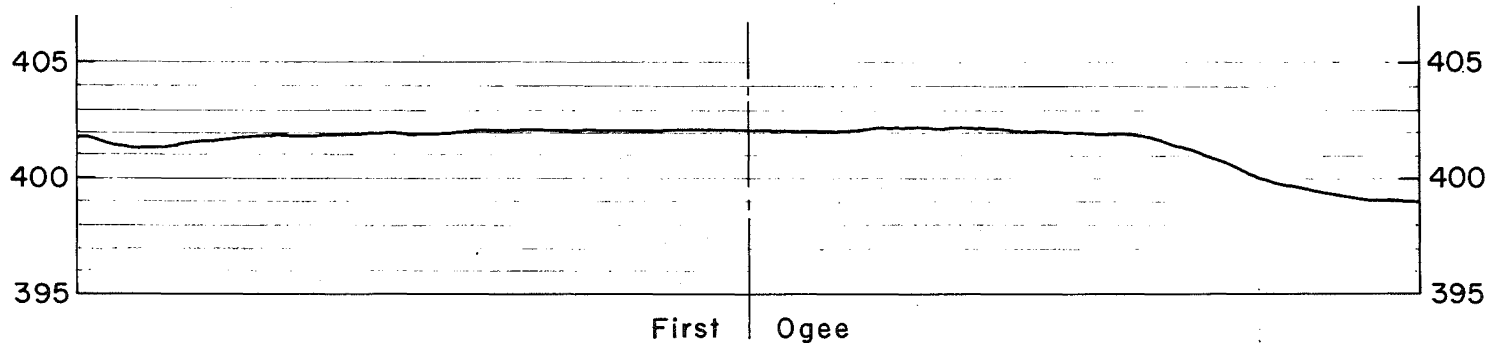
Both Views Looking Upstream

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Original
 Spillway Design - Unmodified
 Design Flow - 40% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-7



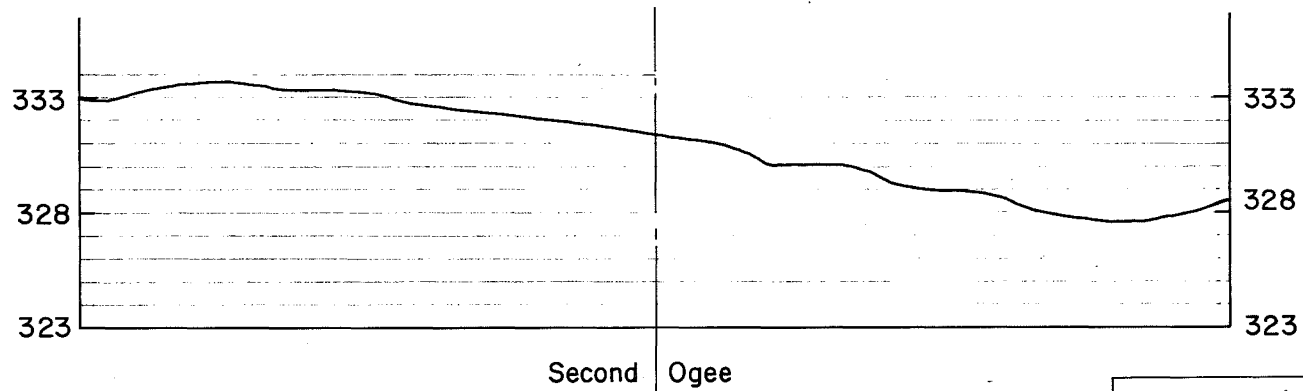
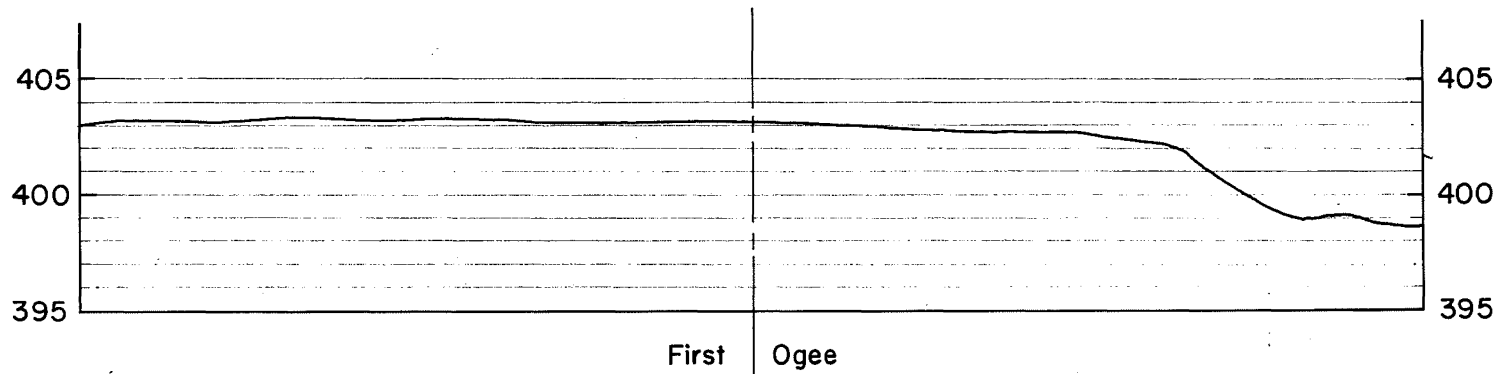
Both Views Looking Upstream

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Original
 Spillway Design - Unmodified
 Design Flow - 60% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-8



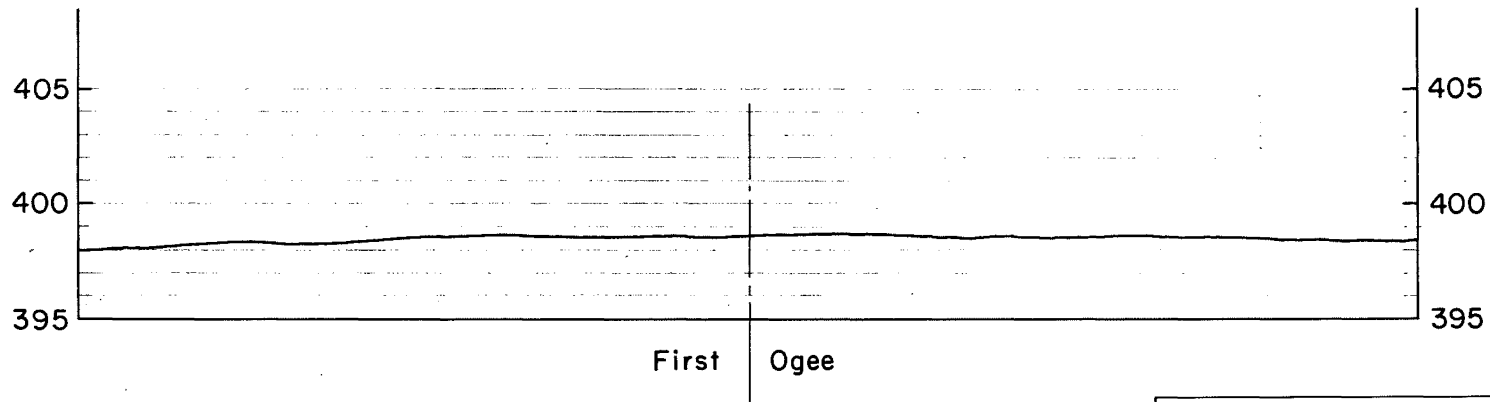
Both Views Looking Upstream

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Original
 Spillway Design - Original Unmodified
 Design Flow - 80% Rough
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. - A2-9



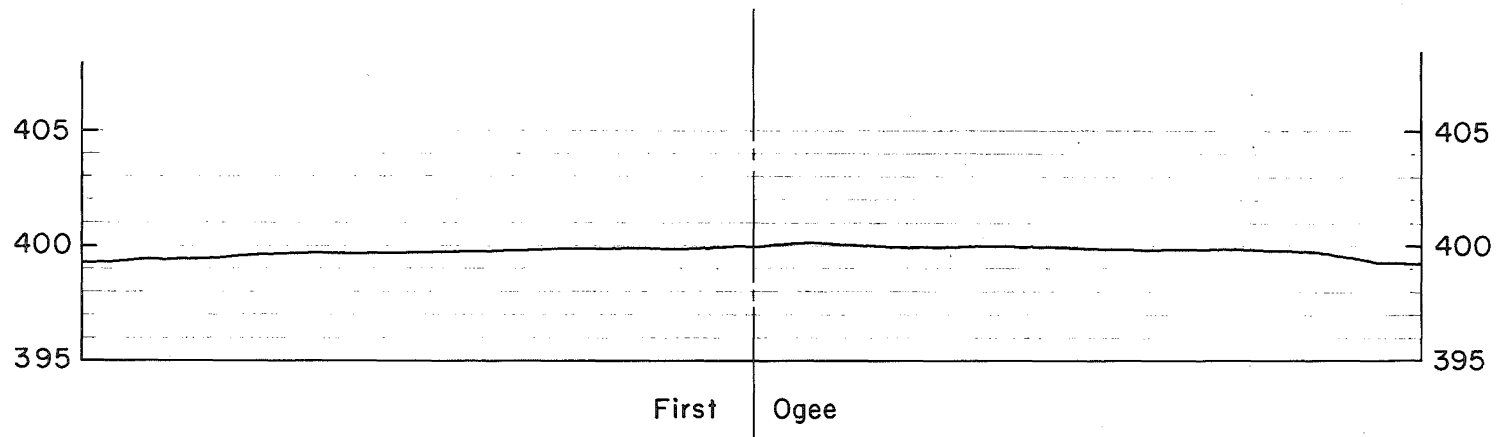
Both Views Looking Upstream

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Original
 Spillway Design - Unmodified
 Design Flow - 100% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-10



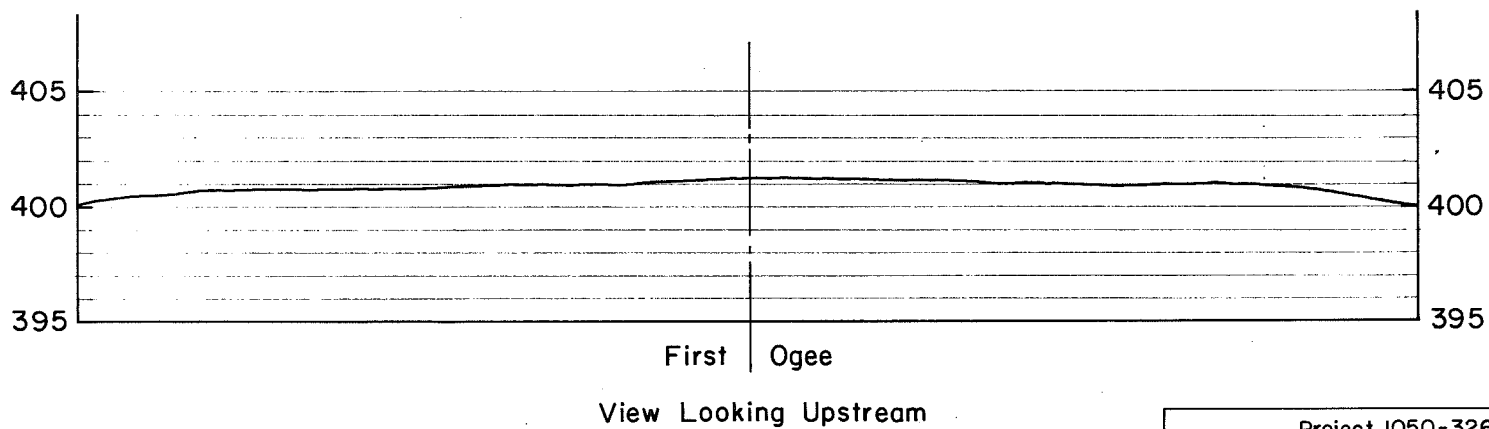
View Looking Upstream

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Modification I
 Spillway Design - Unmodified
 Design Flow - 20% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-11

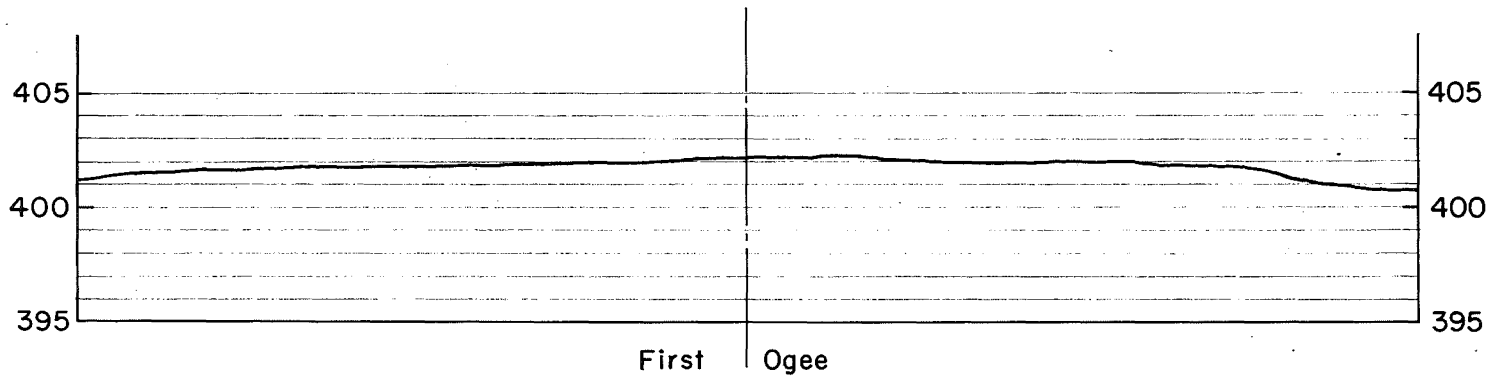


View Looking Upstream

Project 1050-326
NOCKAMIXON SPILLWAY MODEL
First and Second Weir Cross Sections
Forebay Modification - Modification I
Spillway Design - Unmodified
Design Flow - 40% - Roughness
Fritz Engineering Laboratory
Hydraulics Division, Civil Engineering Dept.
Lehigh University; Bethlehem, Penna.
Fig. No. A2-12

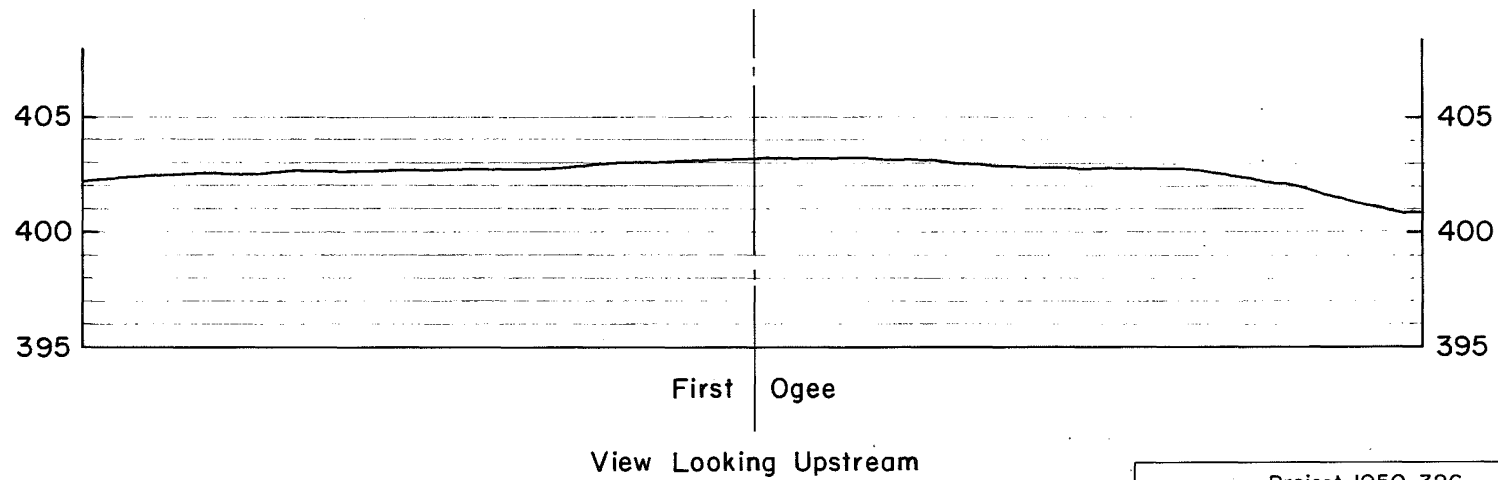


Project I050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Modification I
 Spillway Design - Unmodified
 Design Flow - 60% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-13

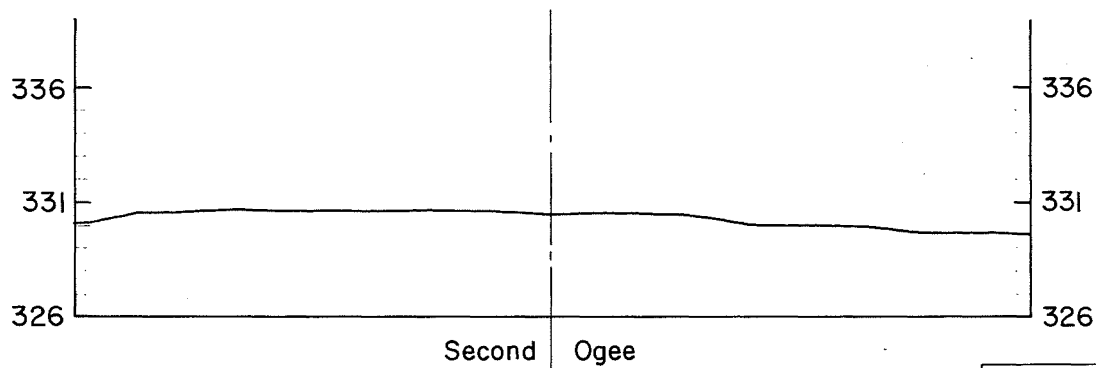
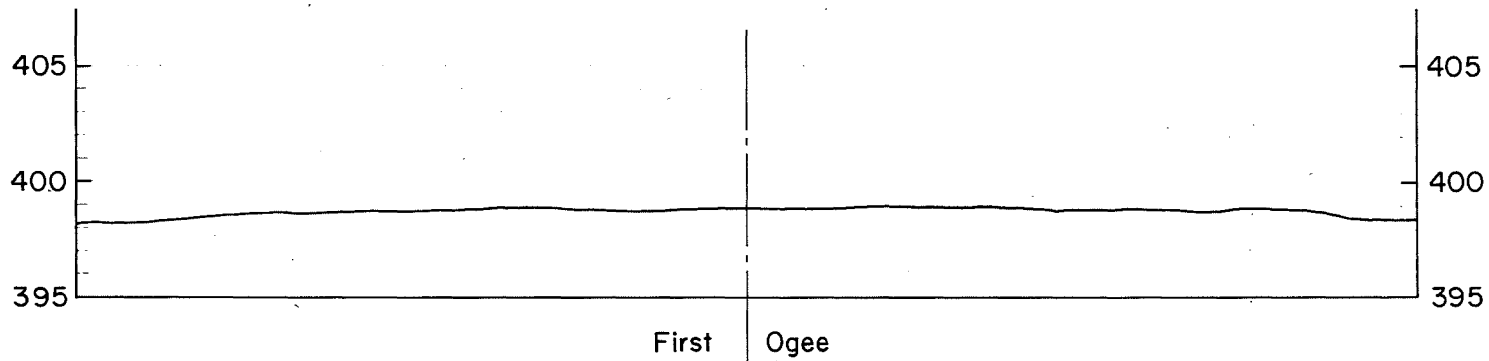


View Looking Upstream

Project I050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Modification I
 Spillway Design - Unmodified
 Design Flow - 80% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-14

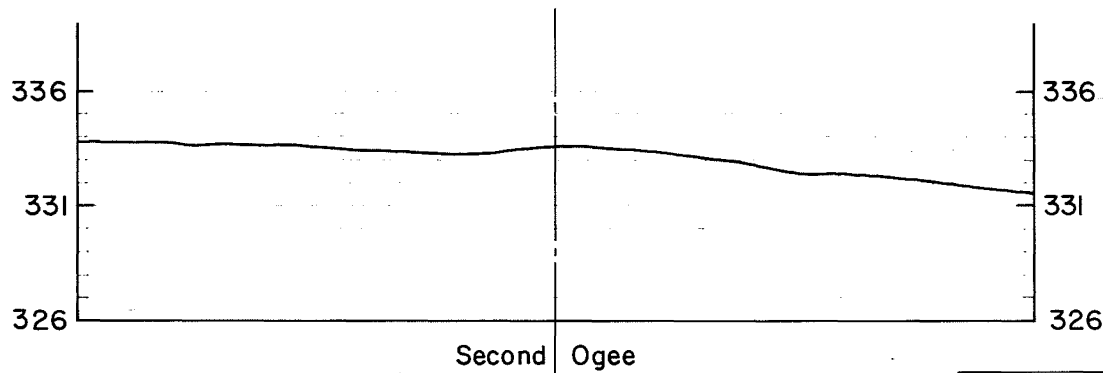
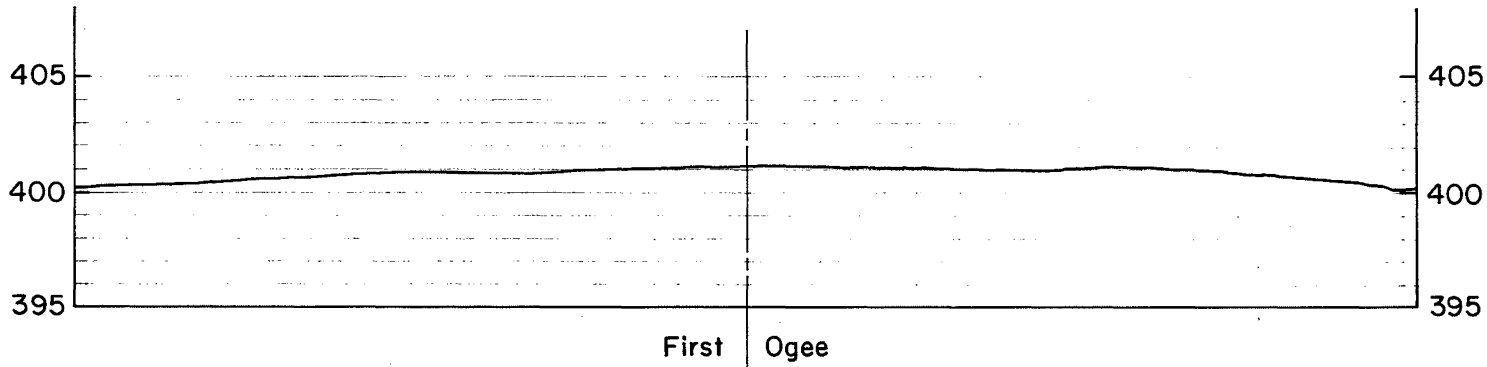


Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Modification I
 Spillway Design - Unmodified
 Design Flow - 100% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-15



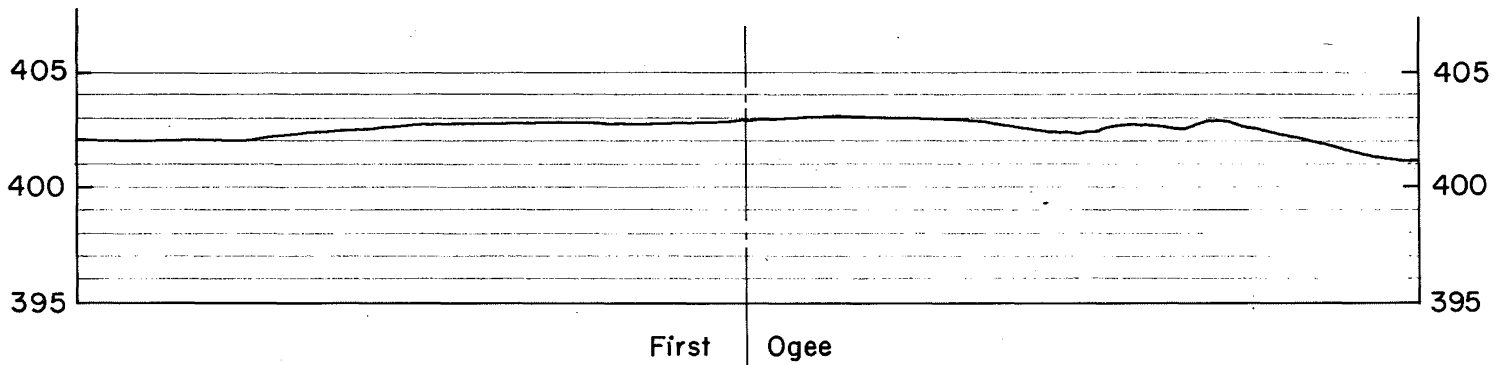
Both Views Looking Upstream

Project IO50-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Modification II
 Spillway Design - Modified Part A
 Design Flow - 20% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-16

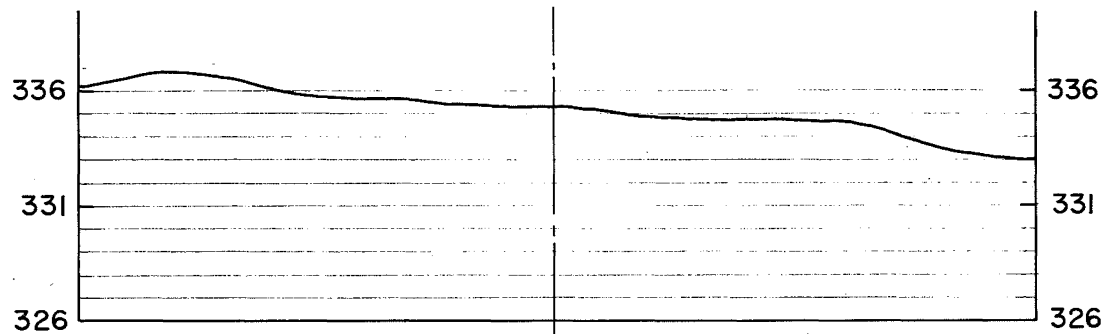


Both Views Looking Upstream

Project IO50-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Modification II
 Spillway Design - Modified Part A
 Design Flow - 60% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division; Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-17



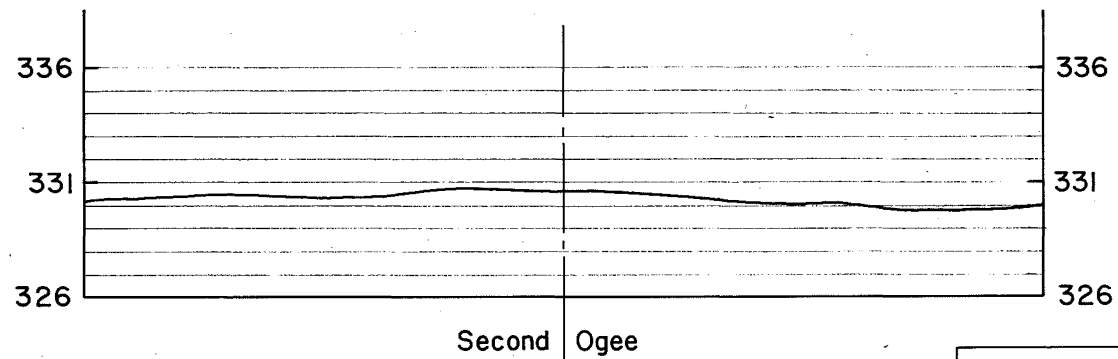
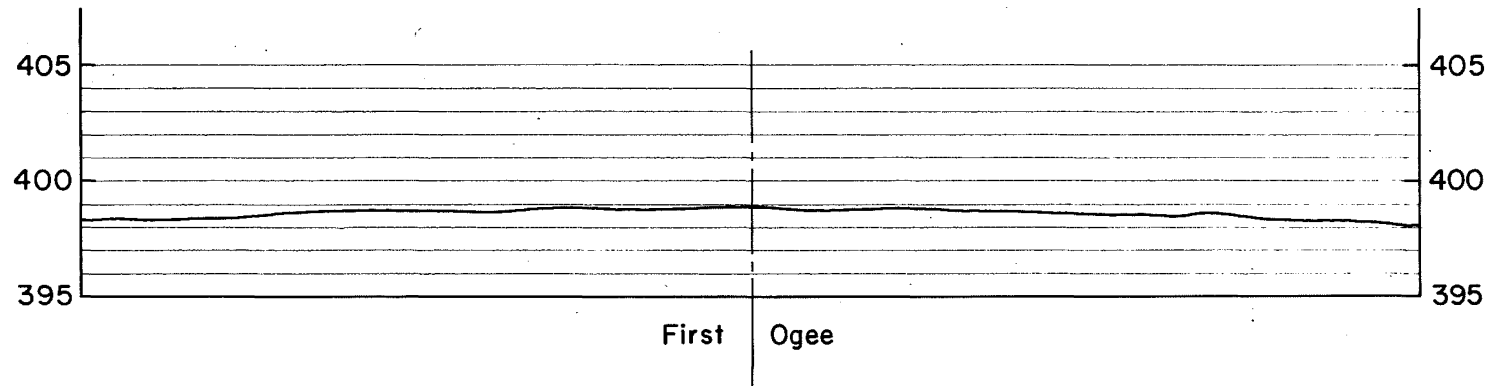
First Ogee



Second Ogee

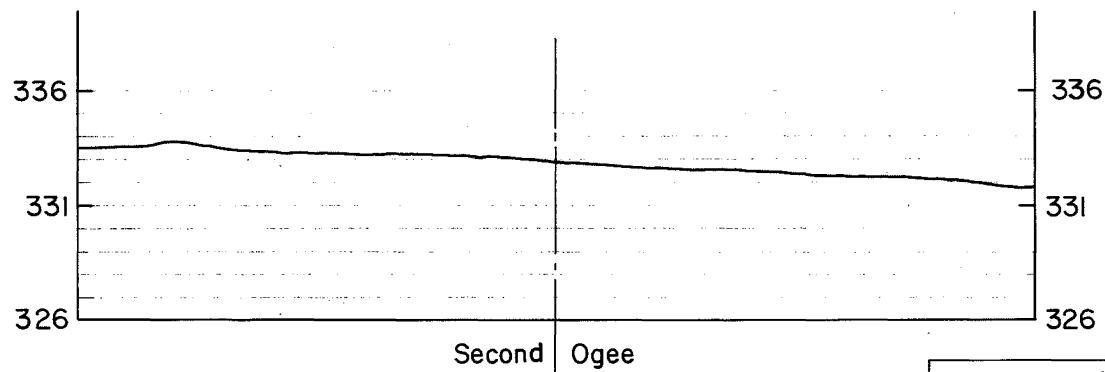
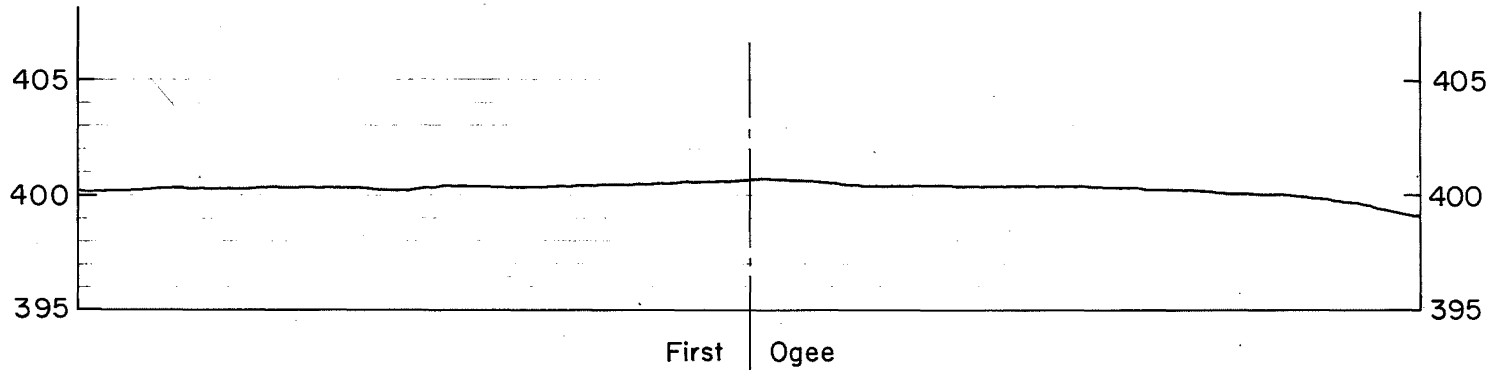
Both Views Looking Upstream

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Modification II
 Spillway Design - Modified Part A
 Design Flow - 100 % - Rroughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-18



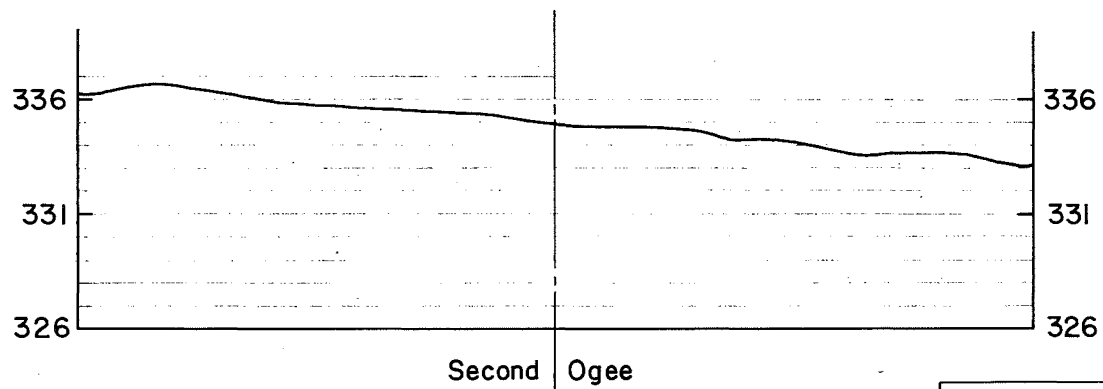
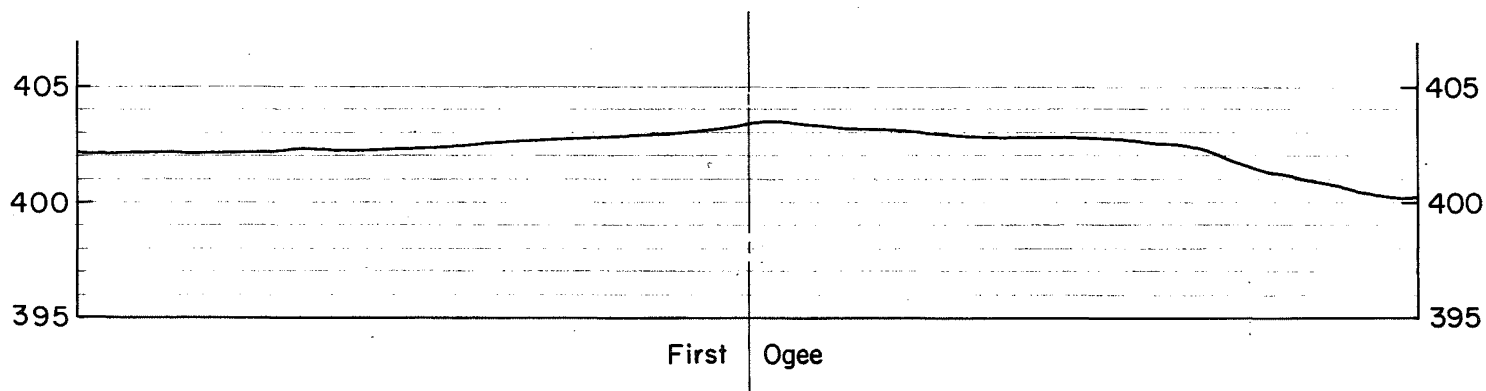
Both Views Looking Upstream

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Modification III
 Spillway Design - Modified - Final
 Design Flow - 20% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-19



Both Views Looking Upstream

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Modification III
 Spillway Design - Modified Final
 Design Flow - 60% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
 Lehigh University; Bethlehem, Penna.
 Fig. No. A2-20



Both Views Looking Upstream

Project 1050-326
 NOCKAMIXON SPILLWAY MODEL
 First and Second Weir Cross Sections
 Forebay Modification - Modification III
 Spillway Design - Modified-Final
 Design Flow - 100% - Roughness
 Fritz Engineering Laboratory
 Hydraulics Division, Civil Engineering Dept.
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 Fig. No. A2-21

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 Department of Civil Engineering
 FRITZ ENGINEERING LABORATORY

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Department of Civil Engineering
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