Hydraulics of River Flow Under Arch Bridges

A PROGRESS REPORT

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INTRODUCTION

Bridges are an integral part of any highway system. The design of a particular bridge depends on many variables. A major consideration, often necessary, is the length of the bridge. In certain circumstances and locations the length may be dictated by factors other than cost. But, where necessary the designer must decide, "How far can the bridge approaches extend onto the flood plain?". The shorter and therefore less expensive the bridge, the less waterway area generally provided. Waterway area is an important problem.

Bridge approaches extending far onto the flood plain decrease waterway area and produce, during high water, a large constriction causing excessive backwater and possible damage to the structure as well as unnecessary flooding of upstream areas. In some cases the state may be held liable for damage to property caused by bridge backwater.

In the past, studies pertaining to backwater caused by constrictions have considered shapes of opening such as that provided by a straight deck bridge. The Bureau of Public Roads has prepared, in cooperation with the Colorado State University, a report, entitled "Computation of Backwater Caused by Bridges."[1] This report in particular considered openings such as are provided by a straight deck bridge.

Fig. 1 is a definition sketch for a normal crossing of the type used in the Colorado experiments. The typical water surface profile is shown as a solid line in view A. The maximum backwater superelevation is designated as h_1^* and the depression of the water surface below

[1] Superscript numbers refer to the bibliography at the end of the paper.

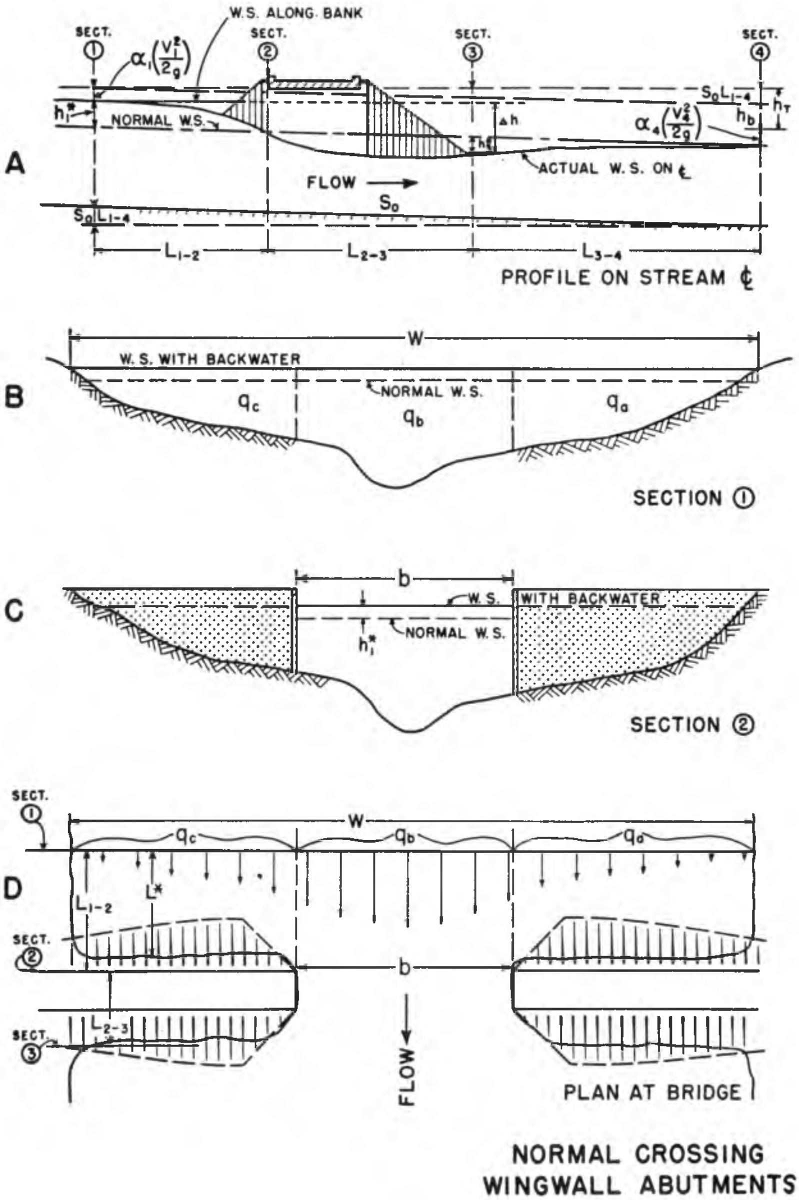

Fig. 1.

the normal downstream of the constriction as h_3^*. View C of the figure illustrates the type opening studied.

Another research project whose subject is both interesting and applicable was carried out by New South Wales University of Technology.[2]

This project was primarily concerned with sharp-edged rectangular openings which produced contraction ratios, m, from 0.10 to 0.95. An equation was presented which gives the discharge as a function of the width of opening head over the opening including backwater, y_1, and C a coefficient depending on m and the Froude Number. This equation makes it possible to determine the backwater if the discharge of the stream is known. Conversely, if the channel conditions are known the discharge through the opening may be calculated by a measurement of y_1.

Very little has been done with arched openings. In short, to the knowledge of the authors, no systematic study has been made of the hydraulics of flow under arch bridges. The arch bridge is unique in that the available waterway area decreases as the depth increases.

Fig. 2 is a picture taken of the 10th Street bridge over Eagle Creek during the flood occurring in the summer of 1957 at Speedway,

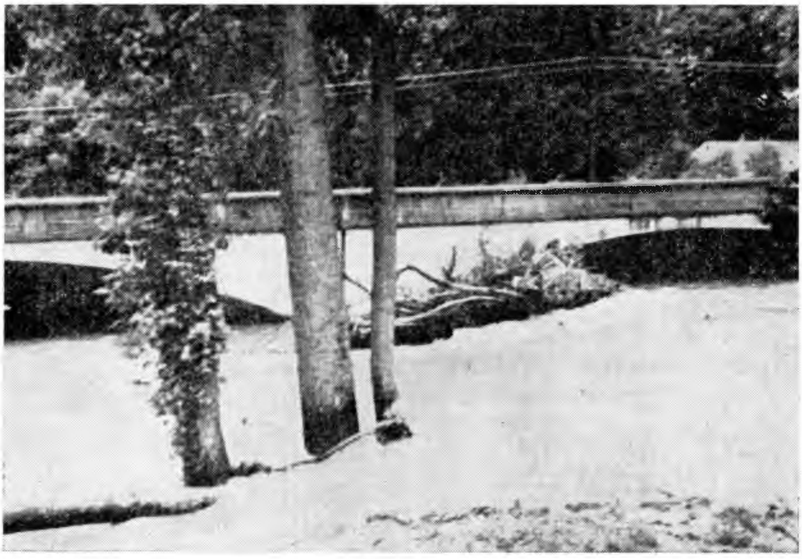

Fig. 2.

Ind. The damming effect of the arch and the accumulated debris are visible. A typical multispan arch bridge subjected to flood flows is shown in Fig. 3. This bridge is the Wayne Street Bridge over the Wabash River at Peru, Ind.*

A project was initiated in the Hydraulics Laboratory at Purdue University to study this problem. It is sponsored by the State Highway

*Photographs courtesy of the Indiana State Flood Control and Water Resources Commission, Indianapolis.

Fig. 3.

Department of Indiana in cooperation with the U.S. Bureau of Public Roads.

PURPOSE

The purpose of the project is to

1. Study the backwater produced by arches and develop a method for their computation.
2. Develop criterion for designing the proper clear span.
3. Study the hydraulic characteristics of flow under arch bridges including:
   a) single span bridges
   b) multiple span bridges
   c) various pier and abutment shapes
   d) shape of arch intrados
   e) discharge and slope of stream
   f) width of bridge.

This paper reports on the first year's work on this project. During this time, a preliminary investigation was initiated. Its purpose was,

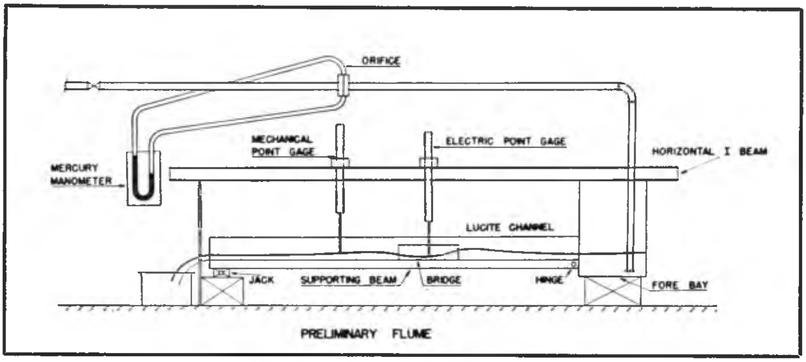
ORIFICE
MECHANICAL POINT GAGE
ELECTRIC POINT GAGE
HORIZONTAL I BEAM
MERCURY MANOMETER
LUCITE CHANNEL
JACK
SUPPORTING BEAM
BRIDGE
HINGE
FORE BAY
PRELIMINARY FLUME

Fig. 4.

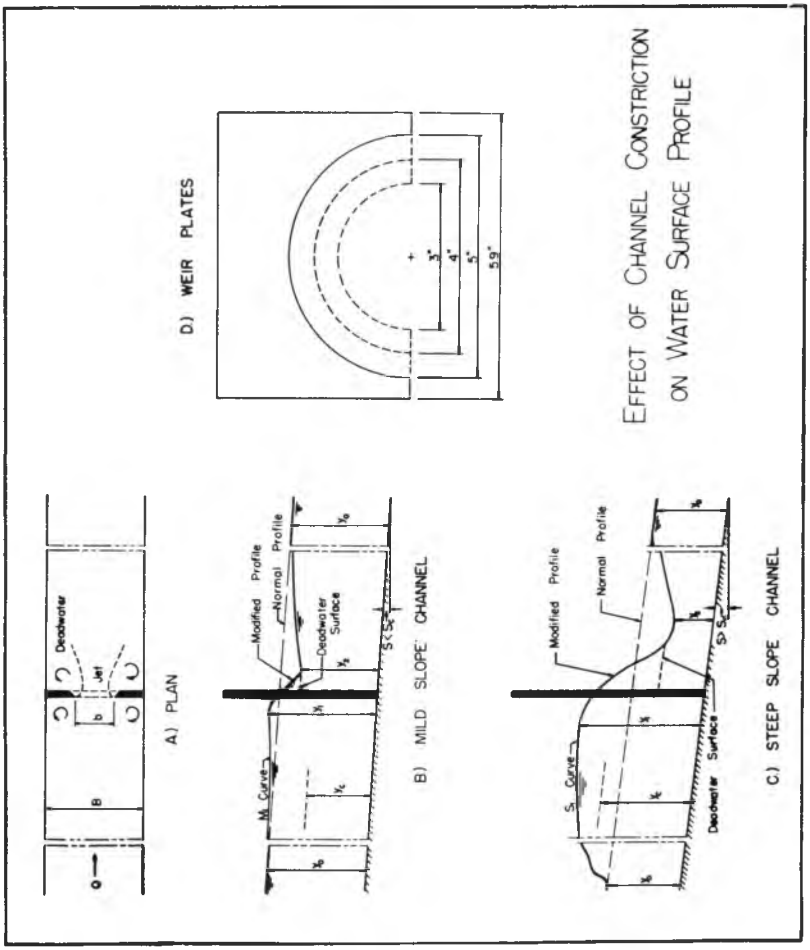
EFFECT OF CHANNEL CONSTRICTION ON WATER SURFACE PROFILE
D) WEIR PLATES
3"
4"
5"
5.9"
A) PLAN
Deadwater
Jet
B) MILD SLOPE CHANNEL
Modified Profile
Normal Profile
Deadwater Surface
C) STEEP SLOPE CHANNEL
Deadwater Surface

Fig. 5.

first, to help in the design of the testing flume, and, second, to help in the design of the experiments to be carried out in the flume. Simultaneously, the design of the required testing facilities was done and the construction of these facilities was started.

SCOPE OF PRELIMINARY EXPERIMENTS:

A dimensional analysis was made to define the important parameters of the flow. These were found to be the Froude Number, the roughness, the contraction ratio and the normal depth of the flow.

For the purpose of the preliminary testing, a small variable slope flume 6 inches wide and 12 feet long was built. Fig. 4 shows the laboratory equipment used in the preliminary testing. To the right of the figure, the forebay is visible. The channel sides and bottom were constructed of lucite and carefully aligned by means of adjusting screws. The slope of the flume was controlled by a jack at the lower end of the flume. An I-beam mounted horizontally above the flume served as a track for the mechanical and electrical point gages used in obtaining the water surface measurements.

An idealized two-dimensional case was investigated by using semicircular weirs with diameter along the bottom as shown in Fig. 5 to represent the arch constriction. Sections B and C of Fig. 5 illustrate the two types of surface profiles obtained with mild and steep slopes. An equation relating the depths upstream of the weir and the discharge was developed:

$$Q = cy_1^{3/2}bA \text{ where } c = c_d \frac{17}{24} \sqrt{2g}$$

$$\text{and } A = \left[1 - 0.1294\left(\frac{y_1}{r}\right)^2 - 0.0177\left(\frac{y_1}{r}\right)^4 \quad . \ . \ . \ . \ . \ \right]$$

The derivation of this formula may be found in reference 3.

The results of the weir tests were put in graphical form by plotting the coefficient of discharge *vs* the Froude Number with the contraction ratio as the parameter. The contraction ratio is defined as the ratio of the weir diameter b to the flume width B. This graph is shown in

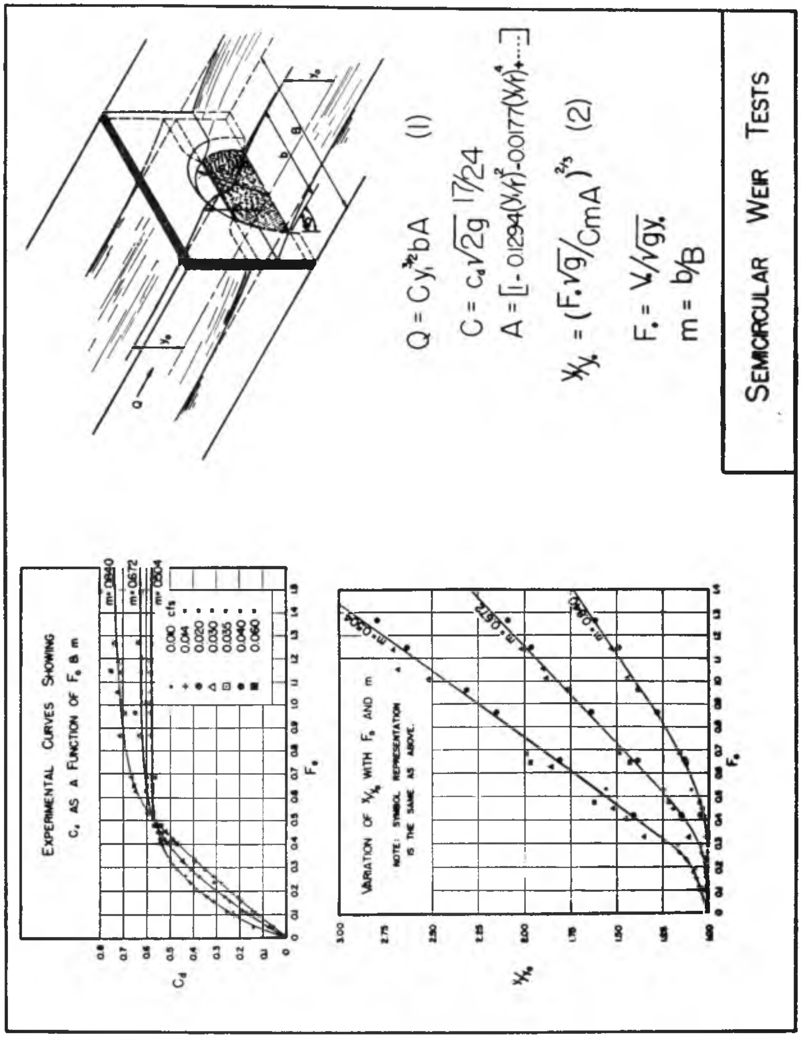

Fig. 6.

the upper left corner of Fig. 6. The lower graph shows the relation of the Froude Number and the ratio of depth upstream of the weir to the nomal depth.

The two-dimensional case was extended to the actual three-dimensional case by using semi-circular arch bridge models of Lucite made to

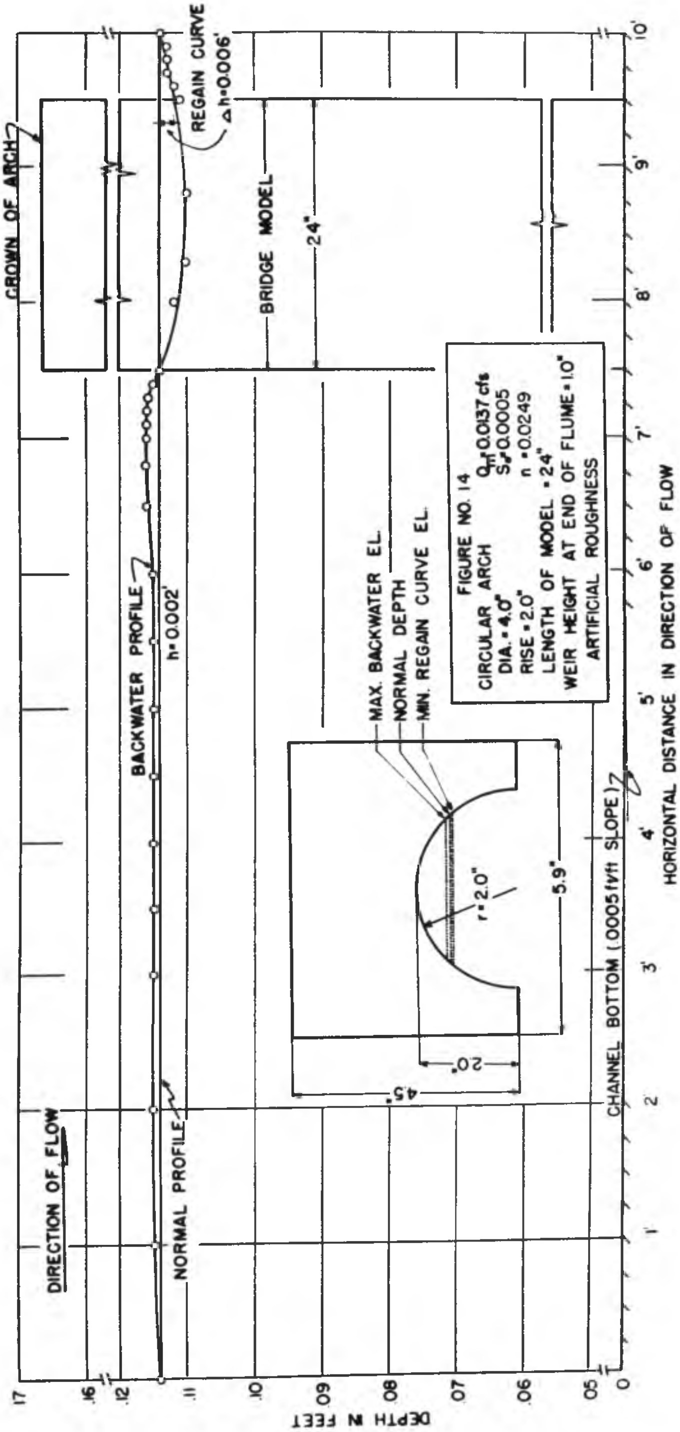
CROWN OF ARCH
REGAIN CURVE
Δh=0.006'
BRIDGE MODEL
24"
DIRECTION OF FLOW
NORMAL PROFILE
BACKWATER PROFILE
h=0.002'
MAX. BACKWATER EL.
NORMAL DEPTH
MIN. REGAIN CURVE EL.
FIGURE NO. 14
CIRCULAR ARCH
DIA.=4.0"
RISE=2.0"
LENGTH OF MODEL =24"
WEIR HEIGHT AT END OF FLUME=1.0"
ARTIFICIAL ROUGHNESS
Q_m=0.0137 cfs
S_o=0.0005
n =0.0249
r=2.0"
5.9"
2.0"
4.5"
CHANNEL BOTTOM (.0005 ft/ft SLOPE)
HORIZONTAL DISTANCE IN DIRECTION OF FLOW
DEPTH IN FEET
.17
.16
.12
.11
.10
.09
.08
.07
.06
.05
0
1'
2'
3'
4'
5'
6'
7'
8'
9'
10'

Fig. 7.

the same contraction ratios. A typical water surface profile observation is shown in Fig. 7. In that case, the flume walls were lined with copper wire mesh of 16 meshes per inch. This gave a Manning's roughness coefficient of approximately 0.025, compared to a coefficient of 0.012 for the smooth boundary. The general test results of the extension of the thory to the three-dimensional case obtained in the smooth lucite channel and are shown in Figs. 8 and 9.

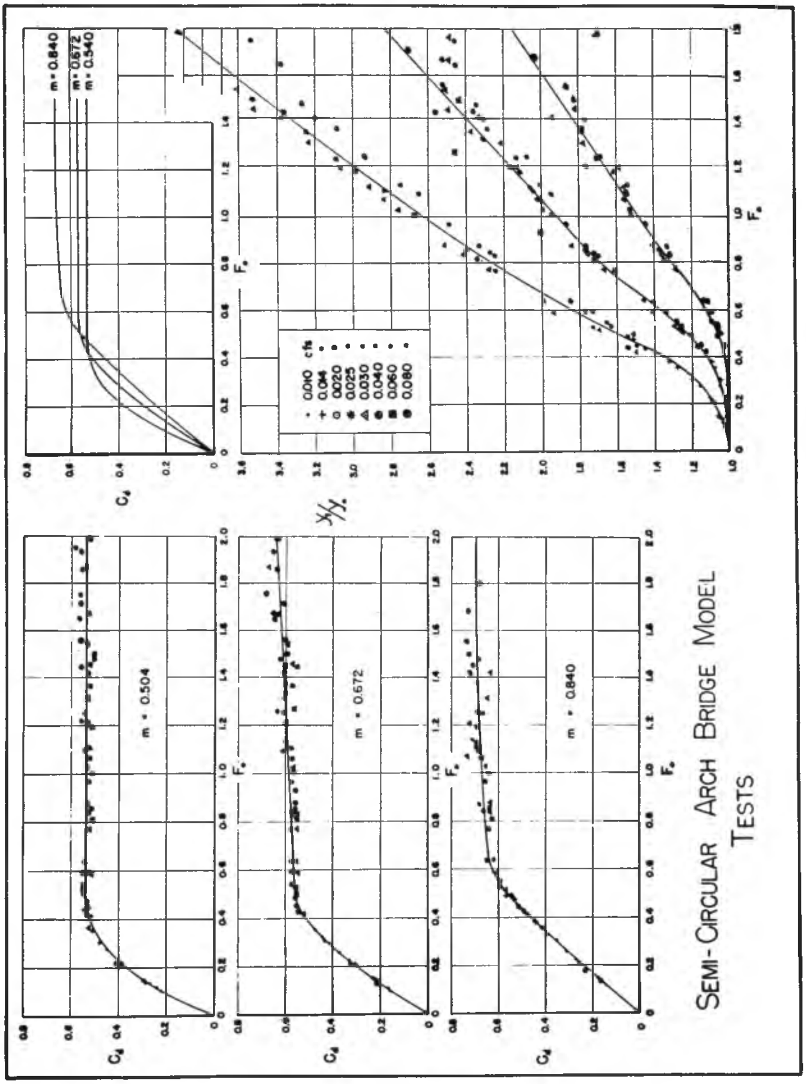

Fig. 8.

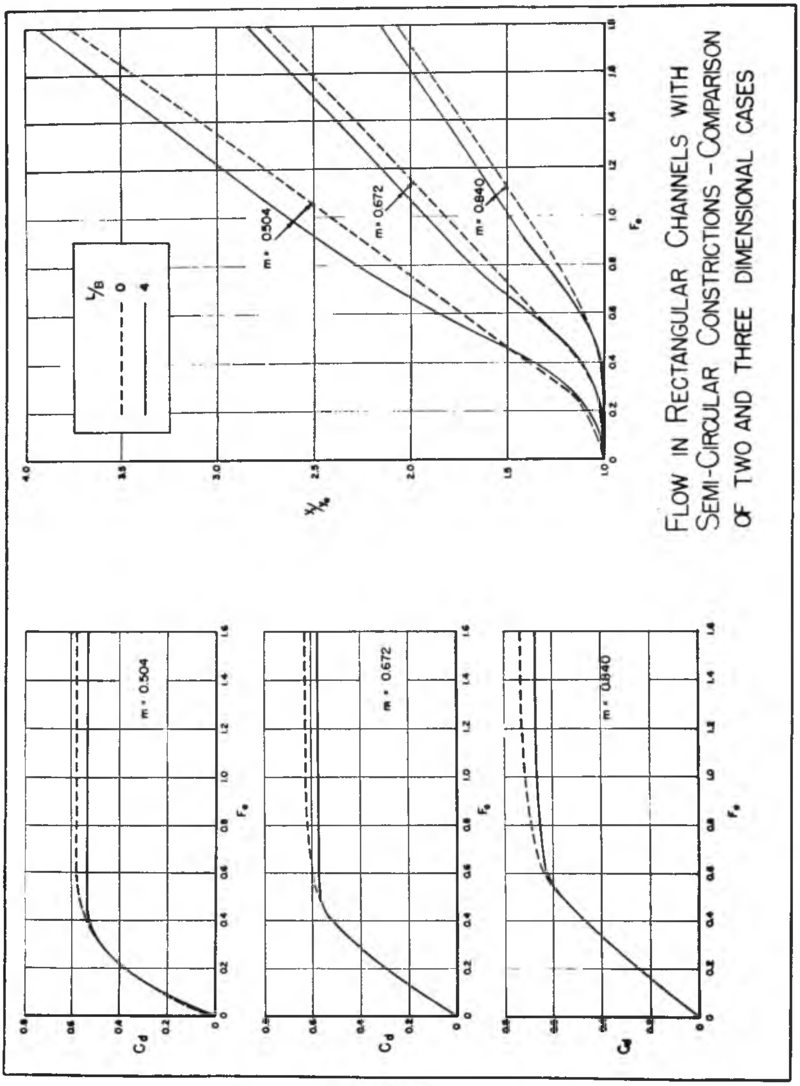

Fig. 9.

Fig. 8 shows the results of the three-dimensional tests, using bridge models of width L = 24 inches. The coefficients of discharge Cd and the ratio of the backwater depth y_1 to the normal depth y_o are plotted *vs* the Froude Number for several values of the contraction ratio m. The results of the two- and three-dimensional tests are compared in Fig. 9. It is interesting to notice that for small Froude Numbers, say less than 0.5, which corresponds to the usual situations in the field, Cd and the ratio $\frac{y_1}{y_0}$ are approximately the same for the two cases. For higher Froude Numbers, the three-dimensional tests exhibit smaller values of Cd and larger values of $\frac{y_1}{y_0}$.

EXPERIMENTAL EQUIPMENT AND TEST PLANS

Simultaneously with the preliminary testing the large flume was designed and is now under construction. The large flume will be 5 feet wide, 64 feet long and capable of 2 feet maximum water depth. The structure is supported on six screw jacks with proportional rates of rise according to their positions. They will be driven by a common motor. These jacks will permit rapid and accurate changes of slope. Provision has been made for widening the channel eventually to 8 feet. Measurements of the water surface will be made from an aluminum instrument carriage mounted on adjustable stainless steel guide rails running the length of the flume. The point gage to be used will be an electric indicating gage reading to a tenth of a milimeter. The flume will be provided with a tailgate control and a discharge control. Measurements of the discharge will be made with two venturi tubes.

The models tested will first be confined to single spans with no skew. Later tests will include other variables. Assuming a typical bridge cross section the scale ratio between model and prototype will probably be from 1:6 to 1:15 for single span bridges.

Fig. 10 shows the arrangement of the equipment in the laboratory and a schematic drawing of the flume. The flume, as shown in the cross section, essentially consists of two I beams for longitudinal support, transverse 6 inch channels and rigidly attached vertical members. The spacing between the channel members is 2 feet. Adjustment bolts are provided for leveling and alignment of the inner channel. The inner channel will be ¼ inch steel plate.

This concludes the work done to date. This is a progress report on the first year of a three-year program.

The expected results in the future include data to compute backwater superelevation for different types of bridges and data to obtain the required waterway opening. The data would be given in the form of design curves for single or multispan bridges and for several shapes of piers and abutments.

ACKNOWLEDGMENT

The project is sponsored jointly by the Indiana State Highway Department and the Bureau of Public Roads and is administered by

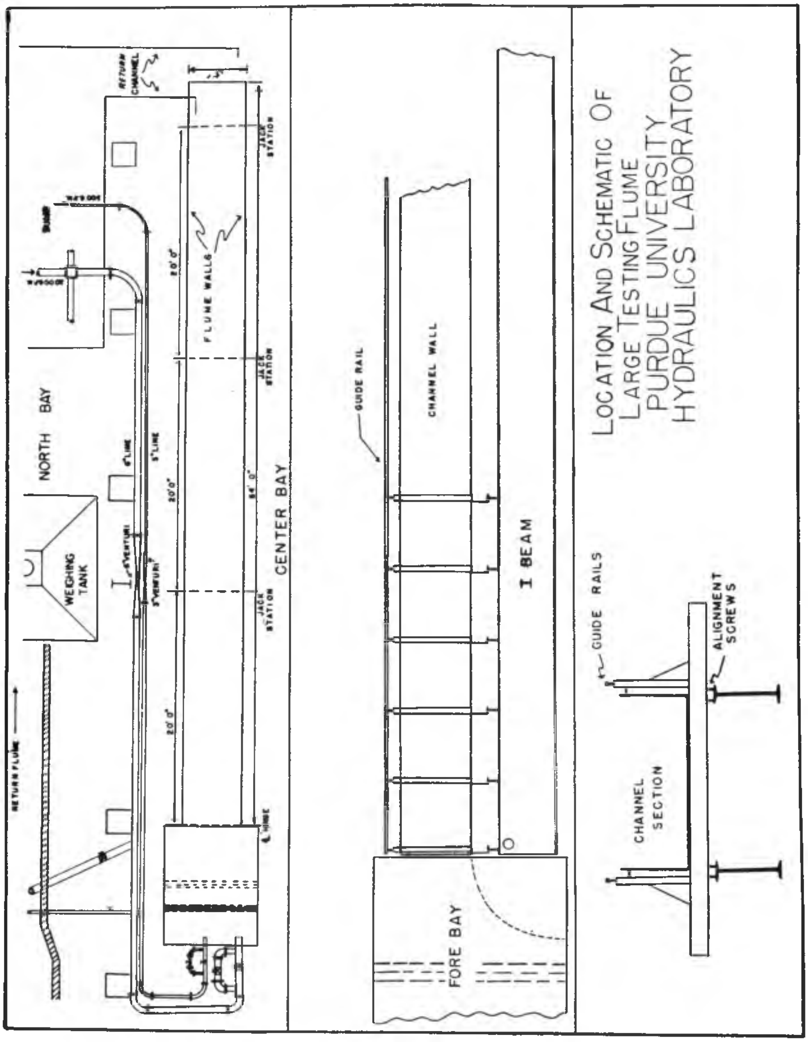

Fig. 10.

the Joint Highway Research Project at Purdue University. The research is under the direction of Dr. J. W. Delleur, Associate Professor of Hydraulic Engineering. Mr. H. J. Owen is responsible for the design of the main testing facilities and the supervision of its assembly. He presented the oral version of this paper at the 45th Road School. Mr. S. T. Husain designed and built the small testing flume and did some observations of the free surface profile. Mr. A. Sooky derived the equation governing the flow in rectangular channels with semi-

circular constrictions and carried out the corresponding experiments including the extension to the three-dimensional case. Mr. P. F. Biery was responsible for preparation of the plates, helped in the experiments and in the construction of both flumes.

BIBLIOGRAPHY

1. U. S. Dept. of Commerce, B.P.R., "Computation of Backwater Caused by Bridges," October 1958, a preliminary draft.
2. H. R. Vallentine, "Flow in Rectangular Channels with Lateral Constriction Plates," *La Houille Blanche,* January-February 1958, p. 75.
3. H. J. Owen, A. Sooky, S. T. Husain, J. W. Delleur, "Hydraulics of River Flow under Arch Bridges—A Progress Report," May 1959, No. 12—Joint Highway Research Project, Purdue University, Lafayette, Indiana.