REPORT ON

MODEL STUDY OF A TRAPEZOIDAL FLUME FOR MEASUREMENT OF STREAM DISCHARGE

Prepared for the

ROCKY MOUNTAIN FOREST AND RANGE EXPERIMENT STATION

by

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January 1960

CER59ARR57

FOREWORD

The results of a model study on trapezoidal measuring flumes with sidewalls having very flat side slopes is reported. Originally developed for the measurement of streams having steep gradients, the flumes were studied under a variety of operating conditions. These conditions included a variation in the upstream roughness and configuration, bottom slope of the structure, and the effect of using an abbreviated design.

The study was conducted in the Hydraulics Laboratory, Colorado State University, Fort Collins, Colorado under the technical and administrative supervision of Dr. A. R. Chamberlain, Acting Dean, College of Engineering and Chief, Engineering Research. Mr. Marvin D. Hoover, Chief, Division of Watershed Management Research, Rocky Mountain Forest and Range Experiment Station collaborated on certain phases of the study. The interest of the Western Soil and Water Management Research Branch, Agricultural Research Service is also acknowledged.

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INTRODUCTION

Two previous reports (1) (3) have been issued dealing with the measurement of flow in channels with steep gradients. The first of these dealt with a 1:7 scale model from which a general design was developed. The second report discussed the correlation of a 1:6 model study with field measurements made on existing structures. A number of tests were conducted on the 1:6 scale model which were not presented in the report.

This report is intended to present the results of all the tests on the 1:6 scale model. These phases cover the effects of: (1) slope of the structures, (2) upstream approach geometry, (3) degree of roughness in the upstream channel, (4) deposits of material within the structure, (5) use of the complete flume in contrast to one with the downstream diverging section removed, and (6) downstream submergence.

DESIGNS AND PROCEDURE

The general design of the flume used in this study is shown in figure 1. The flume, which had sidewall slopes of 30 degrees, was installed in a testing channel 4 feet wide and 2 feet high. The approach channel geometry was varied from a section of these dimensions to one of the same shape and dimensions of the upstream end of the

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trapezoidal flume (noted as approach A and B in figure 1). Flumes operating with the different approaches are shown in figure 2.

The bottom slope of the structure was varied from 0 to 5 percent through an intermediate point of 2.5 percent. After considerable testing utilizing the complete structure, the section immediately downstream from the throat was removed for further testing. The effect of subjergence was noted by using an adjustable tail gate to adjust the level of the downstream water surface.

Water surface profiles were determined throughout the structure as well as upstream and downstream using a point gage mounted on a traveling carriage. Piezometric head was measured at a number of points using hook gage wells. Discharges were measured accurately using either calibrated pipe orifices or a V-notch weir. The location of the point of critical depth was observed and also computed.

ANALYSIS OF DATA

The analysis as presented in this report generally considers the head at two points. These are indicated in figure 1 as h_1 and h_2. Under normal usage, i.e. with a structure of slope 0, the determination of discharge is usually made by measuring the depth at h_1. However, for the design utilizing a bottom slope of 5 percent, only a single measurement at h_2 is generally used. For the purpose of this analysis, data will be presented using h_1 and h_2 separately. No presentation of the theoretical considerations involved will generally be presented.

Slope of the Structure

The slopes used for the structure were 0, 2.5, and 5 percent. Figure 3 shows the relationship of depth in the upstream section (h_1)

to discharge for the three different slopes. These are the results for the flume with the downstream section removed and an abrupt transition (approach A) from the 4-foot wide channel to the flume approach. At a slope of 0 percent an extremely good correlation was found between depth and discharge. This is illustrated by the alignment of data points for this condition shown in figure 3. A slightly higher discharge for a given depth was found when the slope was increased to 2.5 percent. Because of slope, additional kinetic energy is available which results in increased discharge. For a 5 percent slope there was a substantial increase in discharge at constant head. There was also more scatter of the data indicating greater instability of the flow. It should be noted that the relationship of depth to discharge is not a simple exponential one since a curvilinear relationship is indicated on the log-log plot. This is primarily due to the shape of the structure with the control section being a combination of a rectangular weir with a V-notch one.

The relationship using the depth in the center of the throat section (h_2) to the discharge is shown in figure 4. With constant depth, the discharge also increases as the slope increases, but not to the extent as was shown for the depth measured in the upstream position. In this case, a good correlation was noted for slopes equaling 0 and 2.5 percent. However, for a slope of 5 percent there is a transition zone in the area where discharge ranges from 0.28 to 0.70 cfs. The deviations in this transition zone are probably due to the approach velocities changing from supercritical to subcritical as the stage increases. This same effect was noted and discussed in the previous report (3).

Upstream Approach Geometry

Considered in this analysis is the effect of an abrupt transition into the flume as compared to that when the approach section was of the same size and shape as the upstream end of the measuring flume. A third type of approach was also used which combined the effects of an abrupt transition with the trapezoidal section B. This was termed approach C (figure 1) and had sidewalls at 15 degrees from the horizontal with the flat bottom at the same elevation and width of the upstream end of the measuring flume. In essence, the use of different approaches should show the relationship of approach velocity and configuration of flow lines to the head-discharge relationship. For the complete flume with bottom slope horizontal, the relationship was the same whether an abrupt transition was being used or the approach of the same shape as the flume entrance (figure 5). This would indicate that the configuration of the approach channel does not effect the head-discharge relationship for a flume of this design with bottom horizontal. This same conclusion was reached using trapezoidal flumes of several other designs (2).

For the same flume design but without the diverging downstream section and with a slope of 2.5 percent there was a considerable deviation between the rating curve determined with abrupt approach over that with a streamlined one (approach B). There was a sizeable increase in discharge for given head when the flow was approaching through the trapezoidal section. In this case, the difference in approach velocities exerted a major effect.

The relationship of depth to discharge is also shown in figure 5 for the flume without the diverging downstream section and with a slope of 5 percent. There is a very large increase in discharge for a given head (h_1) when the trapezoidal approach section B was being used. Imposed was an additional condition where the approach section was trapezoidal but with sidewalls at 15 degrees to horizontal (approach C). In this case the discharge at a given head was less than when using approach B but much greater than when condition A was used. The velocities were supercritical at the h_1 location when using the two trapezoidal approaches in contrast to subcritical for the abrupt transition. Velocities for all of the other conditions shown in figure 5 were in the subcritical range.

In figure 6 is shown the discharge as a function of depth at the h_2 location for the same cases as shown in figure 5. Here again no change was noted in the relationship for the two extreme cases of approach geometry when the slope was 0. A much smaller difference resulted at the 2.5 percent slope for the two conditions than when using the depth at h_1. The differences in discharge were also smaller when using the three approach conditions at 5 percent slope. The velocities were all supercritical at the h_2 location for all conditions shown in figure 6.

Upstream Roughness

The effect of upstream roughness on the rating is of importance in studying the operation of flume. As reported in a previous study (3) the roughness was varied in order to duplicate field measurements in the model. Figure 7 shows the results with the flume at a 5 percent slope and approach C being used. The roughness was simulated by nailing 1/2-inch high by 13/16-inch wide strips at various spacings to the bottom and sides of the approach section.

There was a considerable difference in the ratings using the h_1 depth depending on the degree of roughness. For a smooth channel, the discharges were much higher and the velocities were in the supercritical range at the h_1 point. Note that the closest spacing resulted in an effectively smoother channel than either of the wider spacings. The 10-1/4 inch spacing resulted in an effectively rougher channel at the greater discharges as indicated by a lower discharge at constant head. At lower discharges the use of a 6-13/16 inch spacing resulted in a rougher channel and a lower discharge. The velocities at the h_1 section were in the subcritical range for all discharges when the roughness was used.

When using the depth at h_2 as the reference, there was a smaller difference in ratings depending on the upstream roughness conditions as shown in figure 8. The use of a smooth channel again resulted in a higher discharge. For the three roughness conditions, the 10-1/4 inch spacing gave the lowest discharge for a given depth. The 3-13/16 inch spacing was found to more nearly simulate the field conditions (3).

Deposits in the Flumes

The effects of deposits of sand and gravel in the bottom of the flume on the rating curve for the structure are important. Since it was determined that deposits would not ordinarily occur for flumes in which the bottom had some gradient, these tests were made only for the case where the invert of the structure was horizontal. The tests were made both when using an abrupt entrance (A) and with a trapezoidal approach channel (B). The small deposit, as indicated in figure 9, consisted of a board 3/4 inch high which covered one-half of the floor in the flume approach and extended into the converging section. In the prototype this would simulate a deposit which was from 4 to 5 inches high. The large deposit was simulated by placing a 3/4-inch board over the entire bottom of the flume approach and extending a short distance into the converging section.

As can be seen in figure 9 there was no discernible changes in the rating curves because of these simulated deposits. This was true for depths measured either at the h_1 or h_2 locations. As pointed out previously, there was also no difference in the discharge for a given head measured at either location depending on whether the flume had a trapezoidal approach or an abrupt transition when the bottom slope was zero.

Complete Flume or Abbreviated Design

A measuring flume without the diverging downstream section constructed as an integral part of the measuring device has been proposed for use where there is no possibility of submergence or where the bed material downstream is not subject to scour. It is necessary to determine the rating of the device and how this may change depending on the absence or presence of the downstream section. For these tests an abrupt approach transition (A) was used, combined with a bottom slope of 0 percent.

Shown in figures 10 and 11 are rating curves depending on whether h_1 or h_2 is used as the reference depth. In the case of h_1, no differences were noted when using the two flume designs except at the lower discharges. In this instance, the flume with the downstream section removed gave slightly higher discharge for a given depth. Conversely, when using the h_2 depth, there was an appreciable difference in the amount of flow at constant depth. Higher discharges were noted for the condition of an abbreviated flume. This would seem to be the result of the critical depth moving upstream resulting in higher, supercritical velocities and lower depths at the point.

Submergence

Flume submergence is defined as the ratio of the depth measured at the h_1 location to that at some point downstream from the control section. In this case, submergence was determined as a ratio of the upstream depth to that in the center of the throat or to h_3 which is near the downstream end of the throat section. This latter point corresponds exactly to that used in a standard Parshall flume for the determination of submergence. For these tests the abrupt approach transition (A) was used, the bottom slope was 0 with a comparison also being made for a flume with or without the diverging section.

The relationship for the complete flume using h_3 as a reference for determining the percent of submergence is shown in figure 12. In the parameter Q/Q_o, Q is the actual discharge and Q_o would be the discharge observed by only a reading at h_1. Since this depth increases as the percent of submergence increases beyond a certain point, the discharge determined by the h_1 depth along is always greater than actual. The ratio Q/Q_o is then a correction factor for determining the true discharge depending on the degree of submergence.

From figure 12 it is noted that a good relationship exists between this ratio and the percent of submergence for all discharges. A correction factor is not needed until the submergence percentage determined at the h_3 location exceeds 70 percent. A deviation of only 3 percent exists at a submergence of 80 percent.

The results for the flume with the downstream section removed are shown in figure 13. The same approach conditions and bottom slope were used. For these tests the effect of submergence varied depending on the discharge. For the higher discharges, a submergence of near 50 percent begins to change the upstream depth. At the lower discharges, the relationship is approximately the same as that determined for all flows through the complete flume.

When using the complete flume, the true discharge can be determined by the use of figure 12. After determining the percentage of submergence, the ratio of Q/Q_o is found. With the reading of h_1 the observed discharge can be determined from rating tables. Applying the ratio to this value results in the true discharge.

DISCUSSION OF RESULTS

A measuring flume necessarily must be adapted to fit a wide range of field operating conditions. For this reason, it is important to understand the effect of these conditions on the rating of the structure. The flume design which is presently being discussed was originally developed for the purpose of measurement on streams with steep gradients. Since it was foreseen that the device might be used in other situations, this study encompassed a wide range of operating situations.

The slope of the structure is of importance from the standpoint of being able to pass large material at high flows. In the case of supercritical flow approaching the structure, high velocities should be maintained through the device. To maintain these velocities it would then be necessary to specify some slope.

In figures 3 and 4 it was shown that the slope of the structure was an important factor in the determination of the rating curve. When the depth was measured at the center of the throat section, there was not as large a deviation as when the measurement was made in the upstream position. At a slope of 5 percent a degree of instability was noted when using the depth at either location. This was in the intermediate flow range and the head-discharge relationship deviated from that for either the lower or higher discharges. This fact would make the determination of a rating curve for a structure on 5 percent slope difficult to determine with great accuracy.

Changes in approach geometry combined with different slopes exerted a major effect on the head-discharge relationship as shown in figures 5 and 6. It should be pointed out that the approach conditions used in this study would simulate the two extremes of approach situations. Normal conditions would necessarily fall between these two extremes. As in the case of slope alone, the best relationship was noted when the depth was measured at the h_2 location. At the 5 percent slope with approaches B and C, supercritical velocities existed in the upstream section of the flume. This in turn materially effected the relationship when using the downstream depth.

The degree of upstream roughness combined with a particular geometry of the channel also exerted a major effect when using the upstream depth. Relatively minor changes were noted with the h_2 position for the relative depth. This was the case for a bottom slope of 5 percent as shown in figures 7 and 8. By analogy, from the discussion of the effect of upstream approach geometry, it could be said that at the intermediate slope these differences would be smaller. Also, when using a structure with bottom horizontal, the head-discharge relationship would be almost independent of the upstream roughness.

For a structure set on zero grade there is always a possibility that sand and gravel may deposit in the upstream section. In effect, this would raise the floor of the structure at the point of deposit. Using simulated deposits fastened to the flume floor it was shown in figure 9 that the relationship did not change from the standard one. This was true for the depth measured at either location. These deposits simulated the field situation where material was deposited to a depth of 4 to 5 inches.

For reasons of economy and where downstream submergence or scour is not a factor, it is possible to use a flume with the downstream section removed. With the absence of this section there was a very small change in the relationship of depth to discharge when using the h_1 reference depth. However, when the depth at the center of the throat section was used there was an appreciable difference in the two ratings. This was shown for a slope of zero in figures 10 and 11. It would be expected that as the slope was increased, the differences in the ratings would also increase.

A good relationship was found between the degree of submergence and the ratio of actual discharge to observed discharge for the complete flume. When the percent of submergence exceeds 70, it is necessary to determine two depths and with these find a correction factor to be applied to the observed discharge. This was the case of a flume with bottom invert horizontal. For the abbreviated design at the higher flows, a submergence of 50 percent or more changes the free flow relationship for the flume. The amount of change is also a function of the discharge. For the lower flows the point of critical submergence is again at 70 percent.

Several general observations were made regarding the general operation of the device depending on the variations in slope and approach situations. At zero slope and low flows the water surface throughout the structure was very uniform and smooth. With the abrupt transition (approach A) there was always a considerable drawdown along the sidewalls as the flow entered the flume. The drawdown increased as the flow increased. At higher flows a large fin formed in the center of the flow throughout the flume. There was also considerable eddying and vorticity along the sidewalls immediately downstream from the entrance. For approach B and slope zero, the water surface was relatively smooth throughout the entire range of discharges.

At the greater slopes the water surface was generally rougher and more turbulence existed in the entrance section. This was particularly evident when using approach B for slopes of 2.5 percent and 5 percent. Except at the very lowest flows, extreme turbulence was noted in the upstream section of the flume for all approach conditions.

Large vortices formed along either sidewall with the velocity component at the boundary in the upstream direction. For the highest flows it was noted that the large vortices changed from side to side. On the opposite side from the vortices the flow surface was relatively smooth.

The position of critical depth within the throat section was observed and also computed for a number of conditions. For the complete flume, with approach A and the slope 0, the point of critical depth was very nearly the center of the throat section; i.e., h_2, and moved downstream slightly as the flows increased. Essentially the same positions were noted when using approach B. For the abbreviated design, at the lower flows this point of critical depth was slightly upstream from the h_2 location. As the flow increased, it moved downstream until almost directly in line with this section.

SUMMARY

For a structure of the general design given in figure 1 there are many factors which may effect the head-discharge relationship. Possibly the most important of these is the slope. With the bottom horizontal, changes in upstream conditions or deposits in the structure did not change the relationship. However, as the slope was increased, upstream configuration and roughness became major factors. In almost all cases, smaller deviations in the depth-discharge relationships were determined when using the depth in the lower section. One exception was the comparison of ratings depending on the absence or presence of the downstream section of the flume. In this case the change was greater when using the downstream location. With the complete flume, the effect of submergence was well defined, whereas for the abbreviated design, this effect varied with discharge.

As the slope was increased there was considerably more turbulence in the flow throughout the structure. With the abrupt transition into the flume there was an appreciable drawdown around the corners and a large fin formed in the center of the flow. There were large vortices and eddies along the sidewalls under this condition.

Although this report presents the study of a model, the results can be projected to geometrically similar structures of any size by the proper model relationships.

REFERENCES CITED

1. Chamberlain, A. R. "Preliminary model tests of a flume for measuring discharges of steep ephemeral streams." Colo. State Univ., Civil Engr. Dept., Report CER57ARC12, February 1957.

2. Robinson, A. R. and A. R. Chamberlain. "Trapezoidal flumes for open channel flow measurement." Colo. State Univ., Civil Engr. Dept., Report CER58ARR39. December 1958.

3. Robinson, A. R. "Trapezoidal measuring flumes for determining discharges in steep ephemeral streams." Colo. State Univ. Res. Found., Civil Engr. Sec., Report CER59ARR1, February 1959.

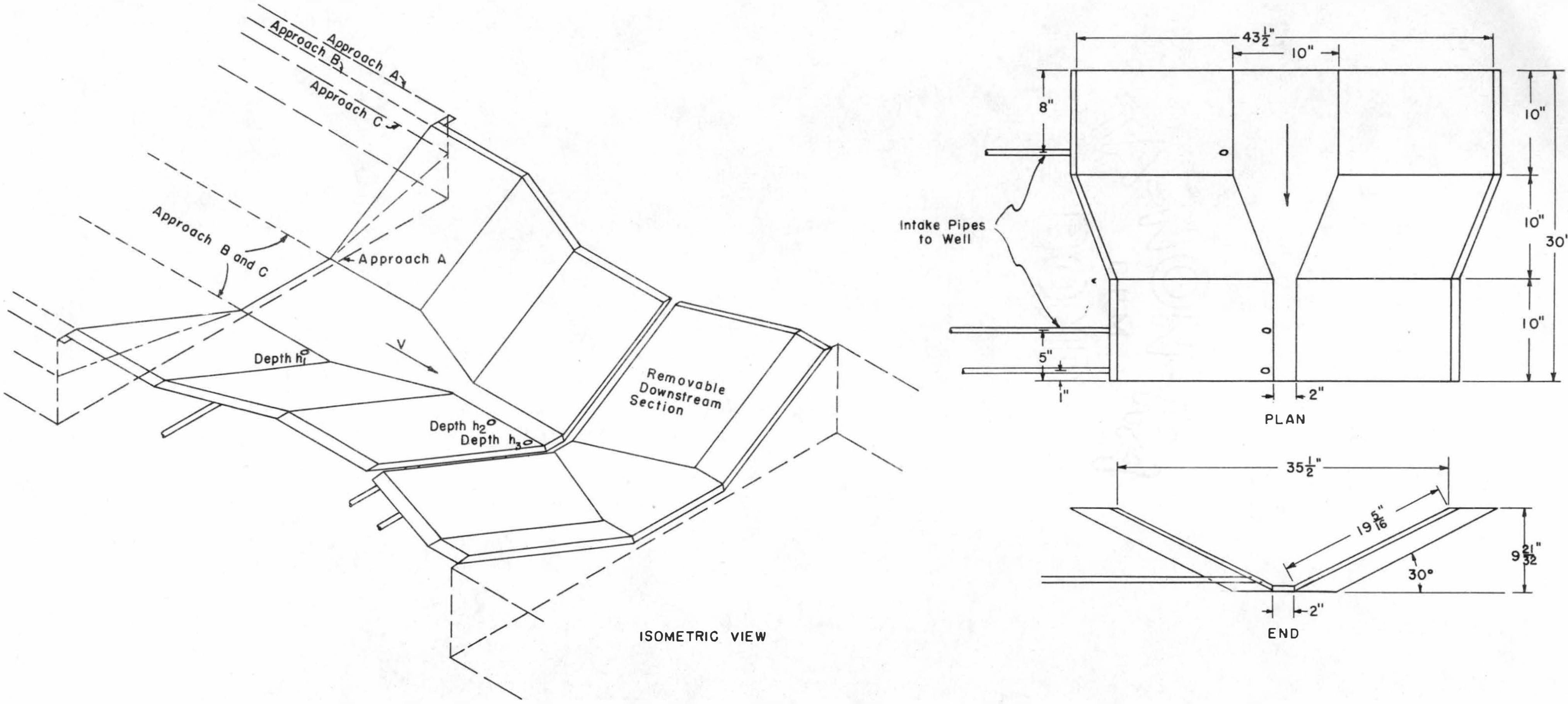
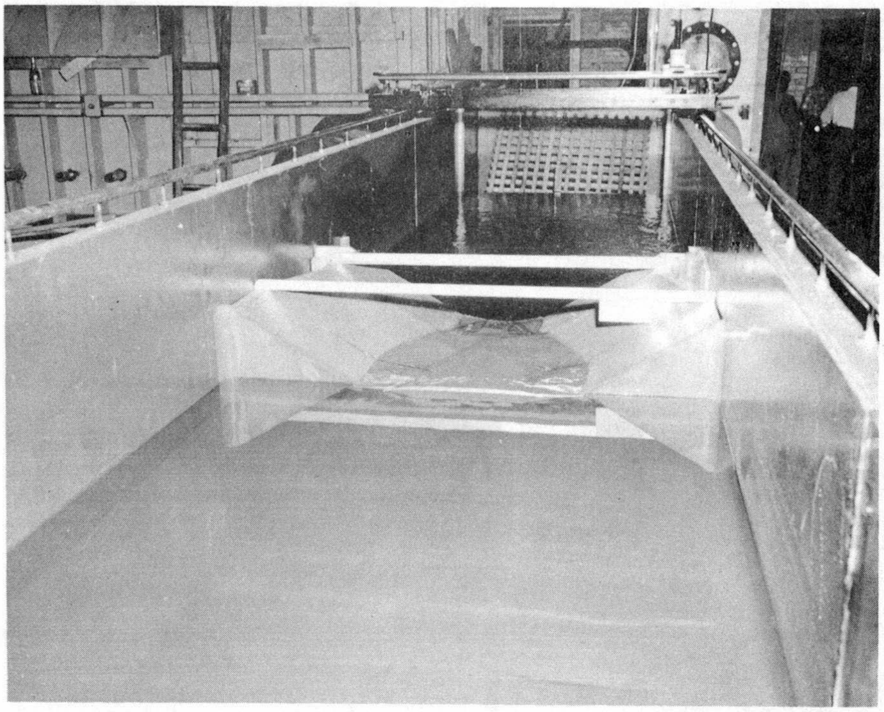
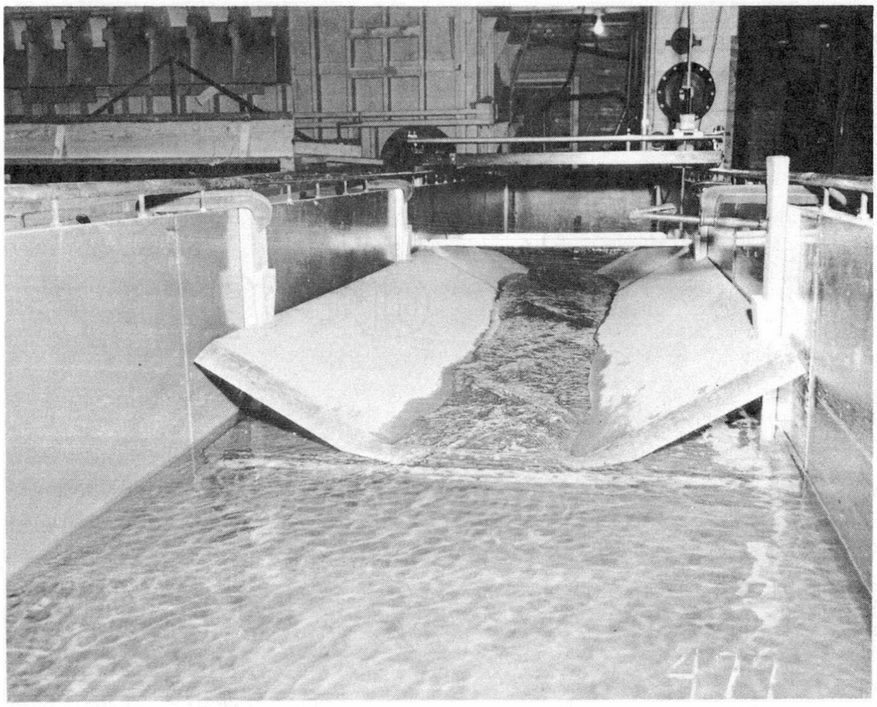


Fig. 1 Flume for flow measurement on streams with steep slopes

Scale 1"=8"



Approach A - Slope 0.0% - Discharge - 0.19 cfs.



Approach B - Slope 2.5% - Discharge 0.27 cfs.

FIGURE 2. FLUME OPERATION SHOWING DIFFERENT APPROACH CONDITIONS.

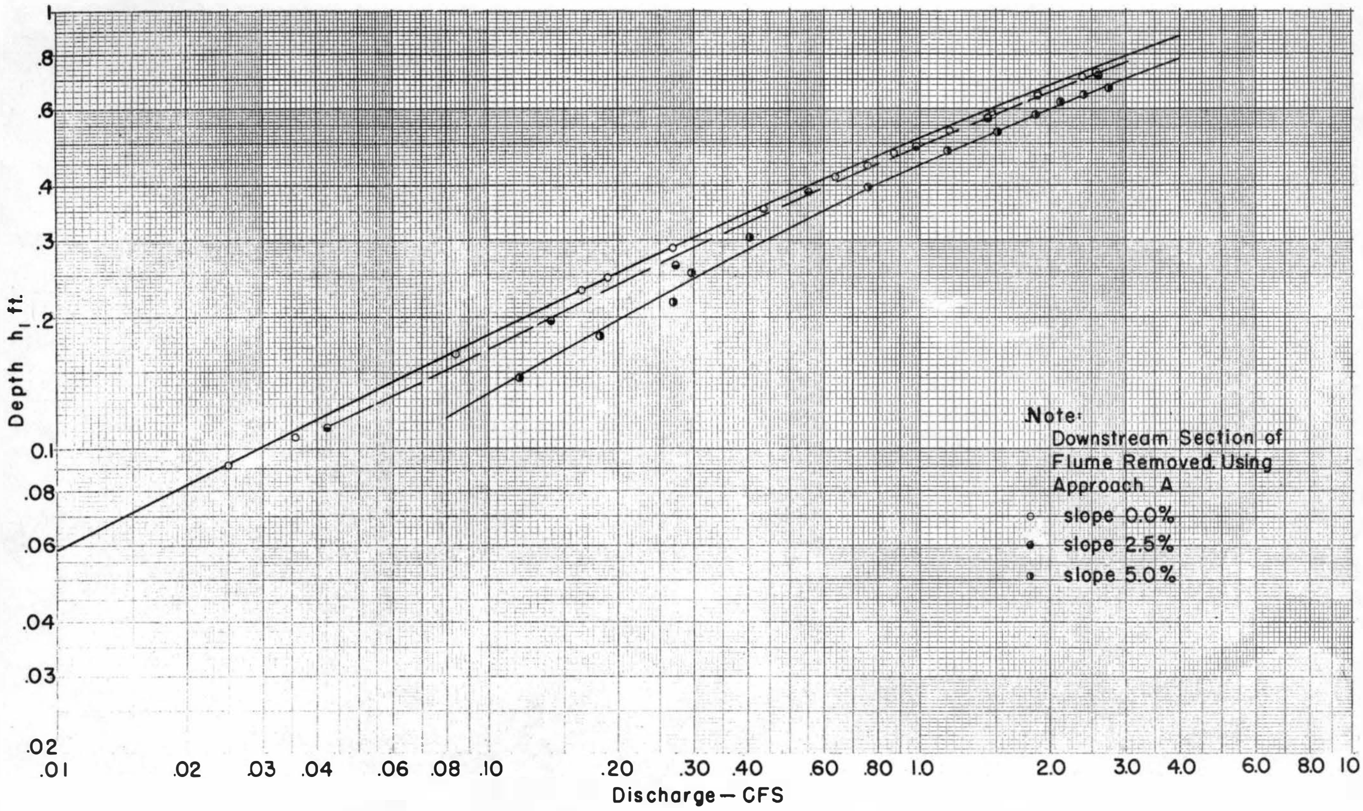


Fig. 3 Effect of Flume Slope on the Depth-Discharge Relationship. Depth in the Upper Section

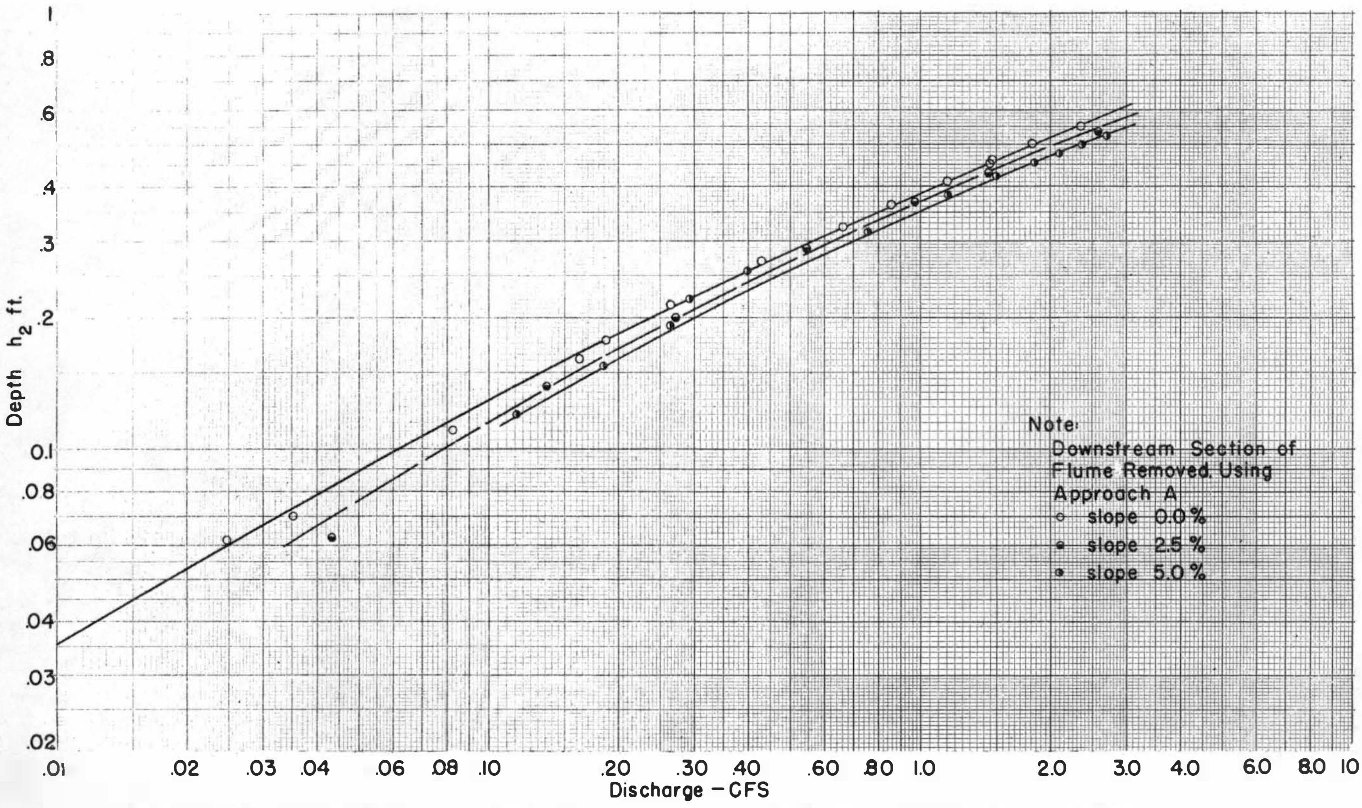


Fig. 4 Effect of Flume Slope on the Depth-Discharge Relationship. Depth in the Lower Section

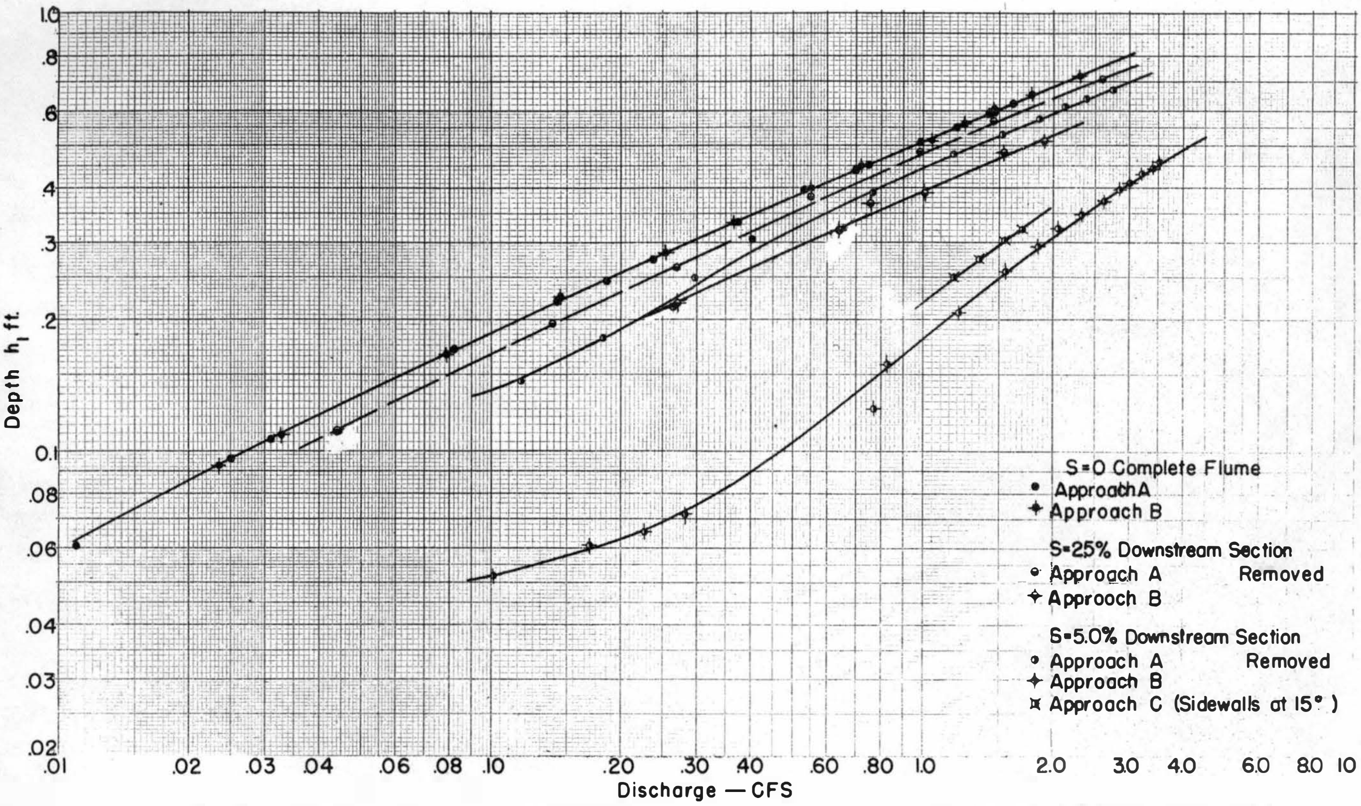


Fig. 5 Effect of Upstream Approach Geometry on the Depth – Discharge Relationship. Depth in Upper Section

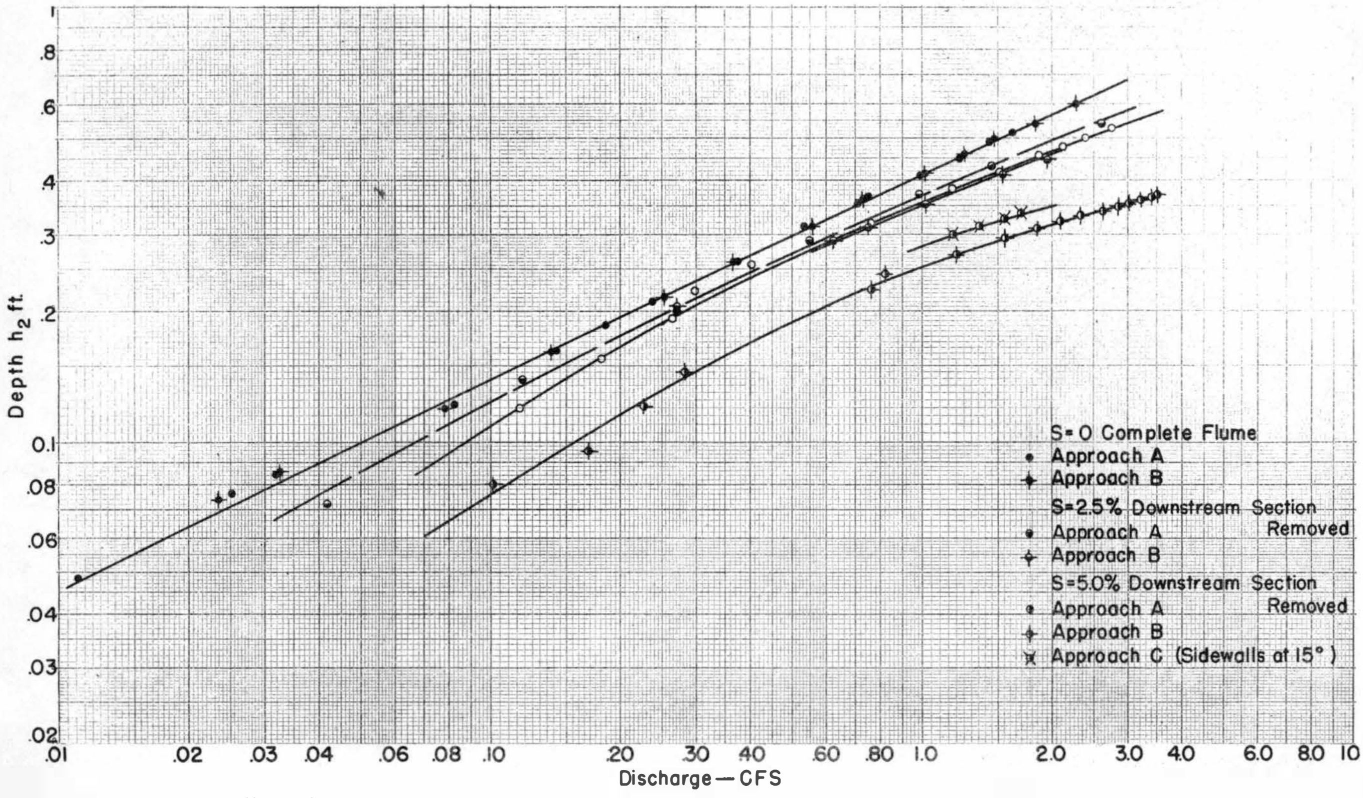


Fig. 6 Effect of Upstream Approach Geometry on the Depth – Discharge Relationship. Depth in Lower Section

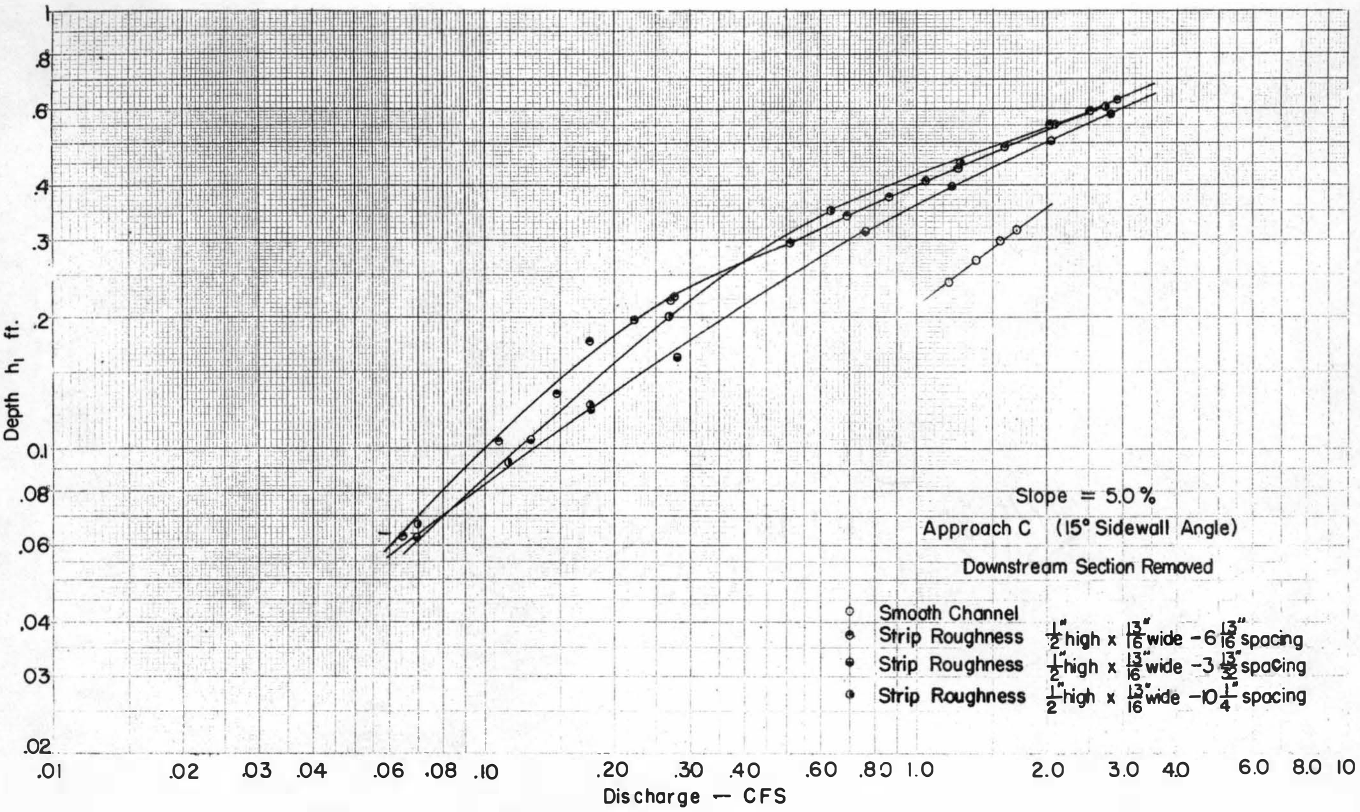


Fig. 7 Effect of Upstream Roughness on the Depth - Discharge Relationship. Depth in the Upper Section

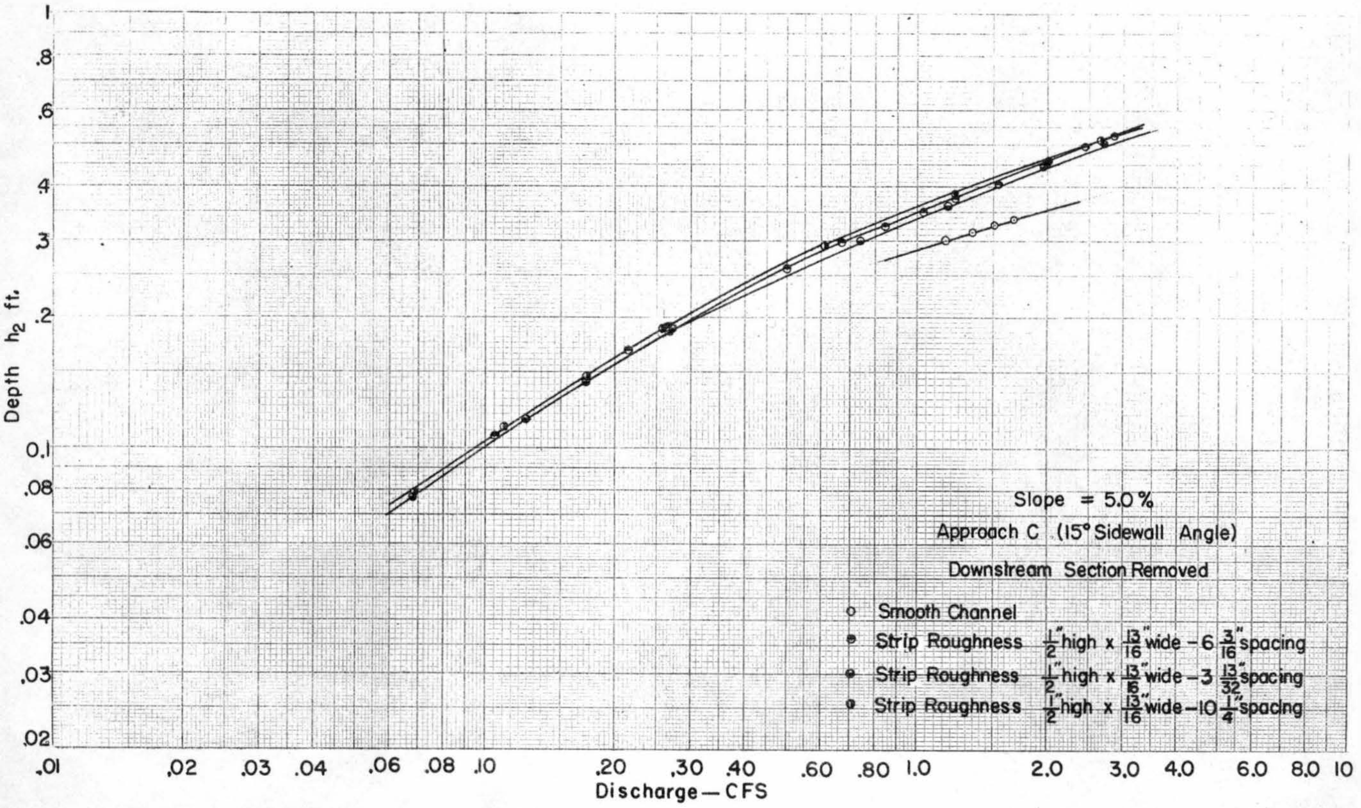


Fig. 8 Effect of Upstream Roughness on the Depth — Discharge Relationship. Depth in the Lower Section

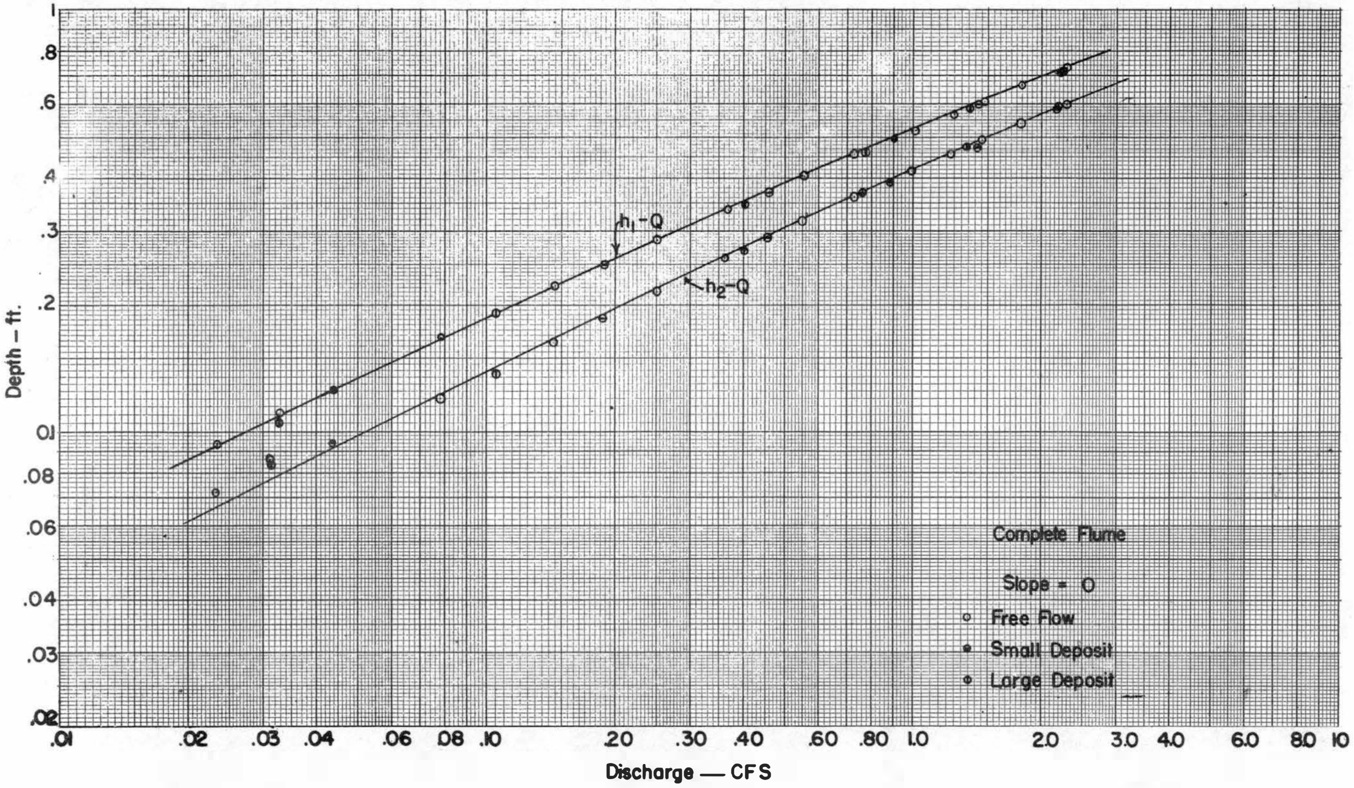


Fig. 9 Effect of Deposits on Flume Bottom on the Depth —— Discharge Relationship. Approach B

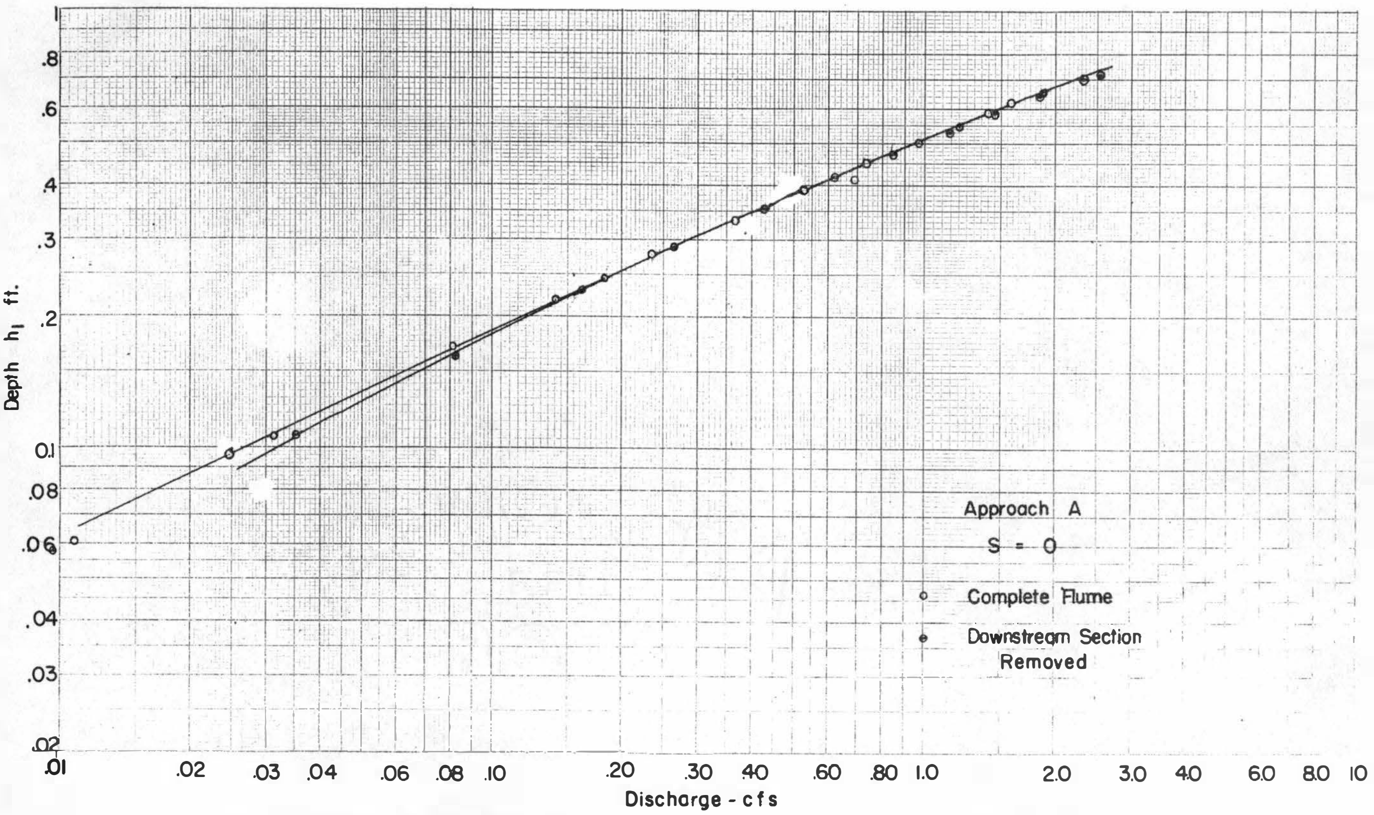


Fig. 10 Effect of Complete Flume or Abbreviated Design on the Depth-Discharge Relationship. Depth in Upper Section.

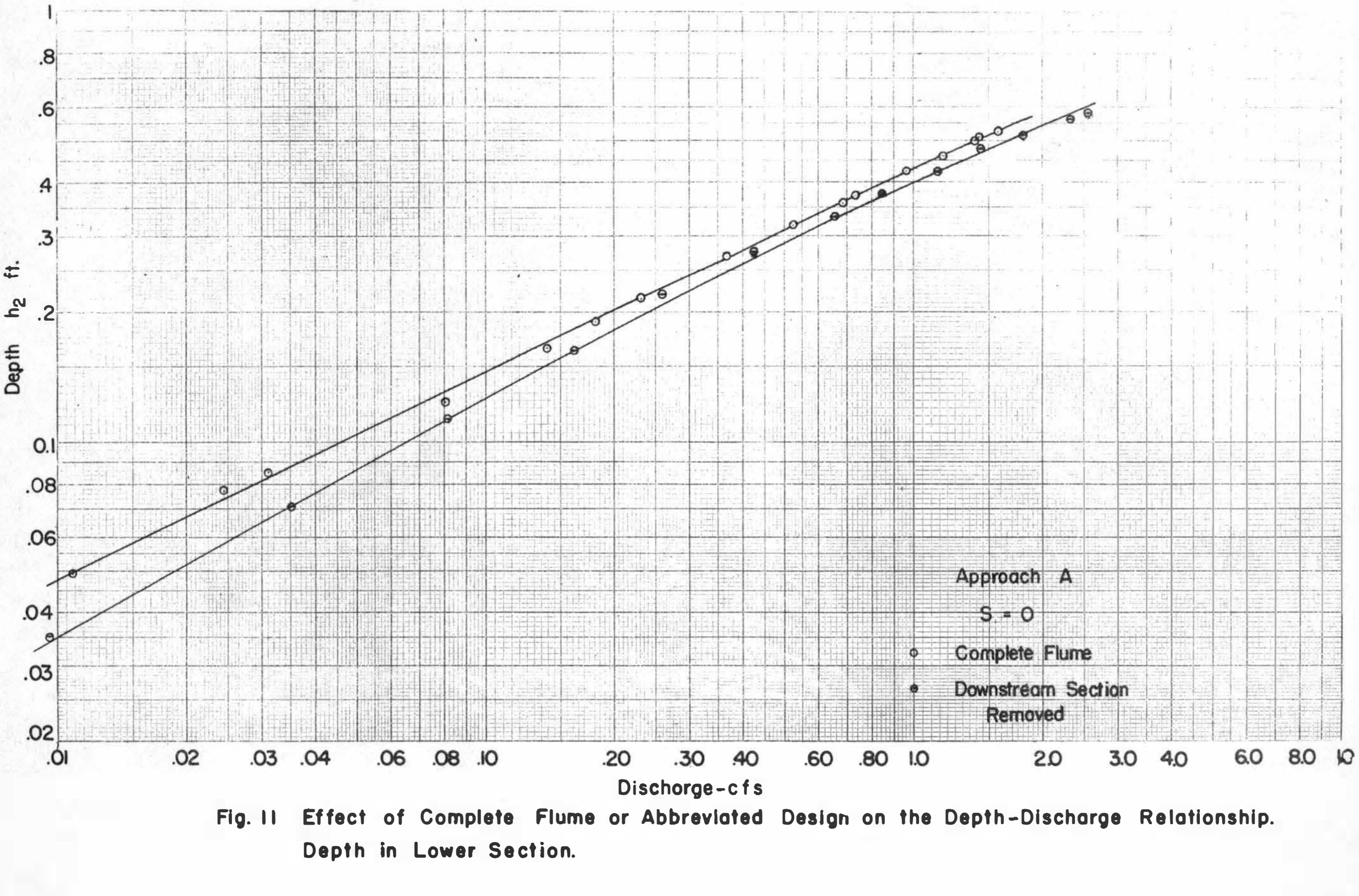


Fig. 11 Effect of Complete Flume or Abbreviated Design on the Depth-Discharge Relationship. Depth in Lower Section.

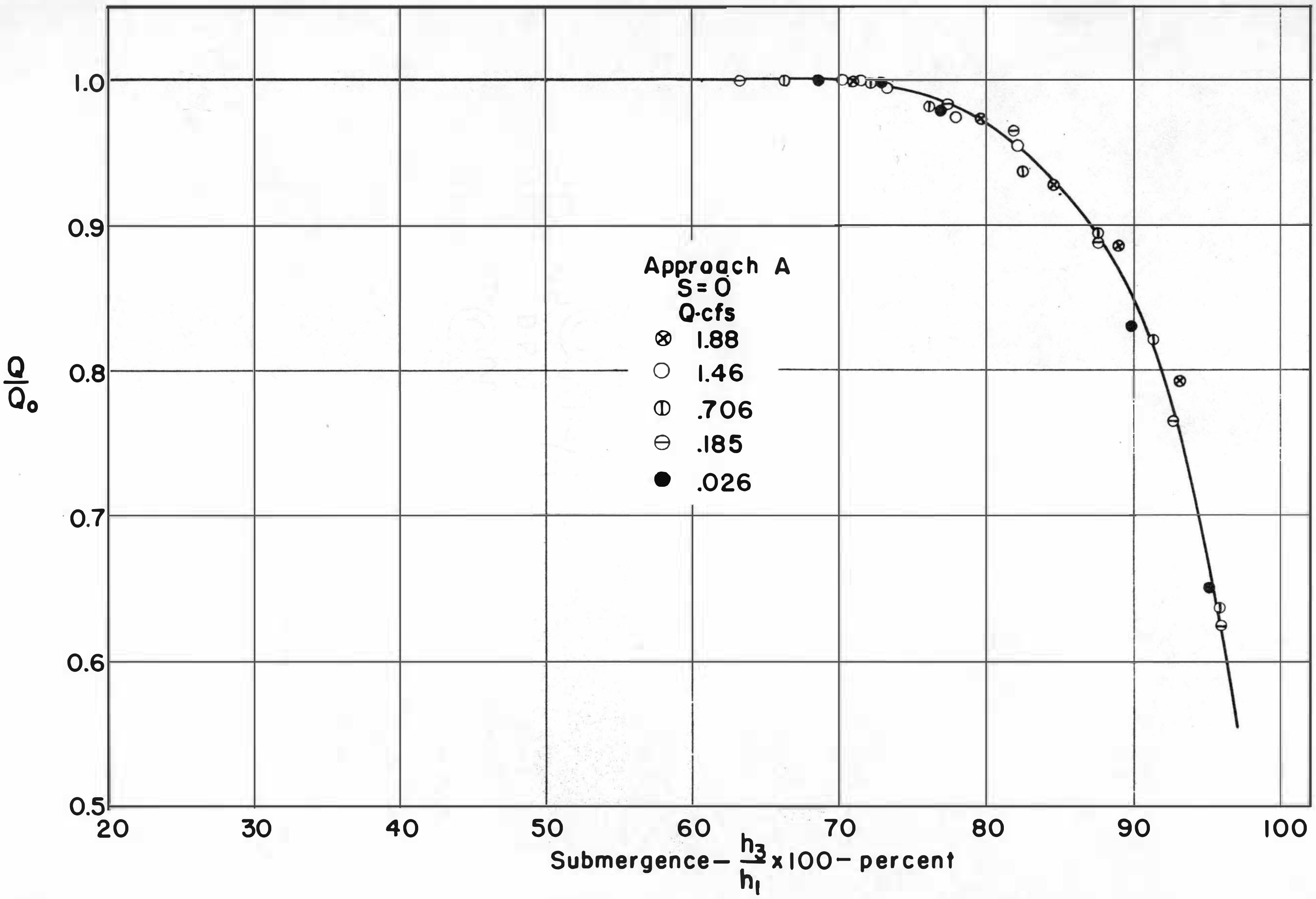


Figure 12 — Effect of Downstream Submergence — Complete Flume

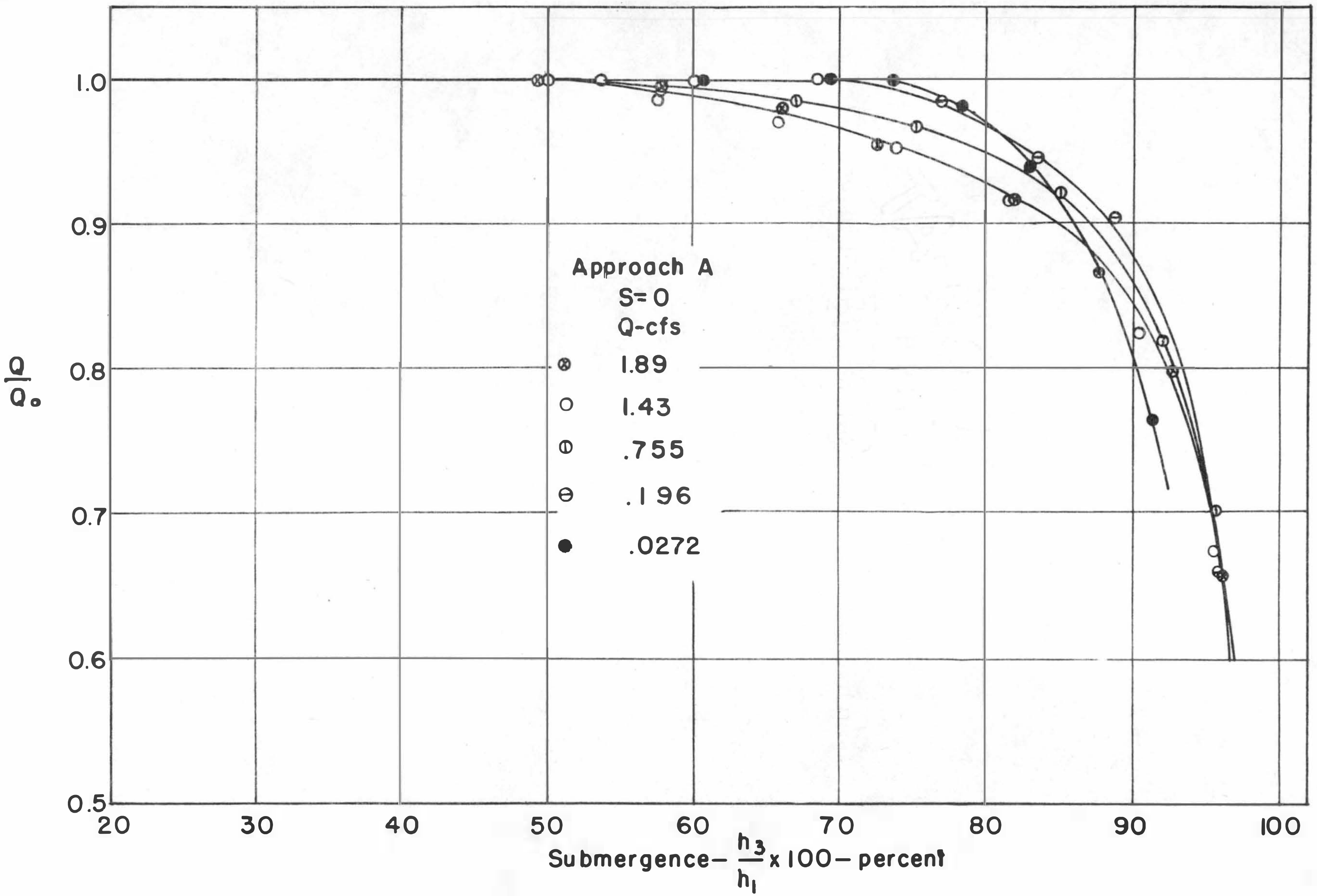


Figure 13– Effect of Downstream Submergence — Abbreviated Flume