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THE EFFECT OF SPUR DIKES
ON
FLOOD FLOWS THROUGH BRIDGE CONSTRICTIONS

by

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by

John B. Herbich, M. ASCE*

I. INTRODUCTION

The highway engineer is confronted with problems of designing bridges, culverts, and other structures to handle flood flows.

Several investigations of scour at bridges in the northeastern United States caused by floods of 1955, were conducted and people began to wonder if washed-out bridges and flooded roadways, undermined culvert aprons, and other evidences of flood damage were really unavoidable. It now appears that much of the damage could be prevented by proper design.

In the State of Connecticut alone the damage in August and October 1955, amounted to about $30,000,000. Fifty per cent of the damage was on State bridges and roads, and fifty per cent on Town and City bridges and roads.

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Because a large percentage of the bridge damage could be attributed to failure of foundations caused by scour, the present study was initiated in 1958. In the past, the bridge superstructures were designed meticulously from the structural point of view, while the hydraulic design of piers and abutments was based on the "rule of thumb". Undermining of structures because of scour is still very much of a problem, especially with the present trend towards high approach embankments to bridges, with consequent deep flood plane flow. The main difficulty with the existing structures which were built 15-20 years ago, is the fact that these bridges, in many cases, contracted the flow excessively.

Scour is also noticeable at the piers and abutments of bridges which are badly located, and especially at points of severe stream curvature, resulting in deep scouring at the outside of the bend. Answers to all of the problems in highway hydraulics are not at hand. In perhaps no other field of hydraulic construction is the designer so handicapped by lack of knowledge of the basic factors involved. However, some progress has been made during the past few years in studying the problem of scour around bridge piers and abutments.

This paper deals with the effect of spur dikes on flood flows through bridge constrictions. A spur dike may be defined as a projection extending upstream from the bridge abutment and which serves to channel the flow of water smoothly through the opening between the abutments (Fig. 1). The spur dike may also be called a guiding dike (i.e., to guide flow between bridge abutments). The advantages of spur dikes are many, and properly designed spur dikes would:

(a) reduce the chances of scour at bridges,

(b) reduce excessive backwater,

(c) allow a greater constriction than otherwise possible, or provide a more efficient waterway.

II. GENERAL COMMENTS

The current practice in hydraulic design of bridges appears to be limited to determining the width of constriction, which would assure mean velocity below the scouring velocity. The constriction of the stream causes concentration of flow in the vicinity of abutments, resulting in higher velocities, and eddying caused by discontinuities in the shape of abutments. The concentration of flow and eddying increases with the increase of contraction (or is a function of percentage contraction = $L_o/L \times 100\%$). (Sketch A).

In view of the formation of zones of eddies adjacent to the abutments, the effective bridge opening is in fact reduced, and the actual velocity higher than the design velocity. In addition to the higher velocity near the abutments, the combination of high velocity and eddy velocity causes scour, undermining of abutments, and eventual failure.

Thus two possible solutions are apparent to provide a more efficient waterway.

(a) provide more uniform velocity distribution through the bridge opening,

(b) eliminate eddying caused by discontinuities in shape of abutments.

III. PREVIOUS STUDIES

The earliest laboratory study of the problem of scour around abutments was a report written in 1894 by Engels in Germany, although reference was made to previous work carried out in France by Durand-Claye in 1873. The Engels study was confined to narrow limits, however, and no attempt was made at generalization nor prediction of scour patterns.

Investigation in this field seems to have lapsed for some years, and it was not until 1949 that a theoretical approach was attempted. The U.S. Department of Agriculture published a paper entitled: FLOW THROUGH DIVERGING OPEN CHANNEL TRANSITIONS(1)*. Also, Posey studied briefly the scour around a pier in the Rocky Mountain Hydraulic Laboratory(2). This was followed by an investigation by the U.S. Geological Survey on COMPUTATIONS OF PEAK DISCHARGES AT CONTRACTIONS, in 1953(3).

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* These numerals refer to listing in the Bibliography

After the disastrous floods in Iowa in 1954, the State University of Iowa began investigations into SCOUR AROUND BRIDGE PIERS AND ABUTMENTS. This work, reported by Laursen and Toch in 1956, was concerned solely with scour(4).

The first study on the effect of spur dikes on the flow pattern in this country, was sponsored by the Georgia State Highway Department. The model spur dikes were made to simulate dikes constructed of timber cribs. It was reported by Carter in 1955, that for spill-through type abutments, a dike of length equal to 0.08(B) (where B = width of opening) at a distance of 0.08(B) from the beginning of abutment curvature, and at an angle of 0° to the flow, proved to be the most efficient(5). No other details were given in the paper.

Following the August 1955 flood in Connecticut, the Connecticut State Highway Department made careful measurements of maximum and average depths of scour and obtained other data relative to maximum high water, mode of failure, debris, and channel characteristics. A formula was developed relating the average depth of scour to the difference between the sediment load in the approach flow and the transport capacity under the bridge(6).

Some studies were conducted in Sweden by Hartzell and Karemyr where dikes were used to align the flow and secure a uniform velocity between the abutments(7). It appeared that a dike some distance away from the abutment and at a 10° angle with the direction of flow, gave best results. However, the tests were inconclusive.

Colorado State University and Lehigh University commenced studies of the effect of spur dikes almost simultaneously early in 1959. The studies at Colorado were conducted in a movable-bed model, while at Lehigh in a fixed-bed model. An elliptically-shaped dike with a ratio of 2-1/2:1 appeared to be most efficient in the Colorado tests. It was also reported(9) that the depth of scour at the abutments is inversely proportional to the length of dike. It was also noted that the scour depth is a function of the percentage of contraction. The design criteria were presented for spill-through type abutments, and tentative guide for determining the length of spur dike was given. In addition, a limited investigation was made for 45° skewed openings. In this part of the study, the depth of scour decreased with increase of length of dike in case of downstream skew, but for the upstream skew, the length of dike did not seem to have any effect on the depth of scour.

IV. EXPERIMENTAL STUDIES

(1) General

The objective of the study has been to determine the shape and size of dikes necessary for generalized conditions, consistent with field conditions. The majority of tests were carried out in a fixed-bed model and necessary measurements of depth, velocity, and discharge taken to permit calculations of Froude Number and velocity distribution in the vicinity and between abutments.

The principal reason for commencing the studies on a fixed-bed model, was the fact that the problem of scour between bridge abutments is a very complicated one, involving a great number of variables. In addition, there is a question of "scale effect" between the movable bed model and the prototype. Employment of the fixed-bed model reduced the number of variables considerably, facilitated the study of velocity distribution, and presented a much clearer picture of the effect of spur dikes on the flow between bridge abutments.

(2) Test Facility

The tank which was available for use in this study was 35 feet long, 10 feet wide, and 2 feet deep, and served as the flood plain across which a constriction could be placed. Flows up to 4 cubic feet per second were utilized.

Vertical forty-five degree wing-wall abutments were selected for this study. The rate of flow was determined from a Venturi meter, velocities were measured, using a midget current meter (Leupold Volpel & Co.), and a propeller meter (Ott).

(3) Limitations and Assumptions

(a) The secondary effect of backwater was negligible, and measurement of backwater effects was not possible in view of the short length of the tank,

(b) The width of tank was not altered during the study,

(c) Flow upstream of the bridge construction was kept below critical,

(d) A constant-rate flood flow was assumed.

(4) Preliminary Studies

Early studies included variation of length of abutments (or percentage opening) and discharge. Velocity and depth data were obtained for bridge openings with and without dikes. Surface particle path lines were obtained from photographs(10).

(a) Basic Idea:

The basic idea involved placing the spur dikes along the streamlines to divert the flow smoothly towards the abutment opening.

It will be noted, however, that the streamline pattern varies with the discharge, and consequently dikes would have to be constructed for the highest discharge, and assumption made that the dikes so placed would produce satisfactory flow conditions for lower discharges. The tests indicated that the dikes eliminated the separation at point B but at high rates of flow, marked separation and eddying occured at point C.

To avoid this condition at point C, very short dikes, called "stub" dikes, tangent to the line BC were found to be very effective. (Sketch B)

(5) General Studies

The basic study involved bridge crossings of the flood plane at right angles, or 90-degree approach, and 60-degree skewed approach (Fig. 1, 2).

(a) Basic Ideas

(1) An improvement in the uniformity of the velocity distribution across the opening, a removal of flow separation, and a reduction of eddying, reduces scour at the abutments.

(2) Spur dikes are designed so that:

(i) a more uniform velocity distribution is achieved across the opening,

(ii) no hydraulic jump is formed along the abutments,

(iii) no separation of flow occurs at the abutments.

(b) The following were the test variables:

(1) percentage opening (L/L_o x 100%). Data obtained for the following L/L_o values:

90° Approach	60° Approach
22.9	22.9
34.6	34.6
43.7	49.6

(2) Length of dike (L_d): 18", 27", and 36".

(3) Dike angle (α):

90° Approach	60° Approach
0°, 10°, 20° and 30°	0°, 15°, 20° and 25°

Discharge (Q) was constant for the majority of tests, and straight dikes were used to simplify analysis. Additional tests involved change in discharge and curved, rather than straight, dikes.

V. TEST RESULTS

(1) 90° Approach

(a) Figure 3 presents meter rpm data (or velocity) versus the distance between abutments, obtained for an opening of 22.9%. Data were obtained across the opening abutments for a bridge without a dike, and with dikes of various lengths (L_d) installed at various angles (α) to the abutments. A considerable improvement is observed in the velocity distribution, particularly for $\alpha = 10°$.

(b) Figure 4 presents data for opening of 34.6%. Improvement is observed in the velocity distribution, particularly for $\alpha = 10°$.

(c) Figure 5 presents data for opening of 43.6%. Improvement is observed in the velocity distribution for all α's.

(2) <u>60° Approach</u> - Spur dike at downstream abutment only.

(a) Figure 6 presents data for opening of 22.9%. Velocity measurements were obtained across the opening between abutments along three lines: A (BF), B (centerline), and C (CG) (Sketch C). At Line A, a decrease in velocity is observed near the downstream abutment, but an increase near the upstream abutment. A considerable improvement is observed near the downstream abutment at Line B, and a general improvement in velocity distribution across the abutment at Line C, when a spur dike is employed. The pattern is similar for dike angles of 0 and 15 degrees. The length of dike does not appear to be an important variable in this case.

(b) Figure 7 presents data for opening of 34.6%. Improvement is observed along the downstream abutment at Lines A, B, and C for dike angles of 0 and 15 degrees.

(c) Figure 8 presents data for opening of 49.6%. Improvement is observed across the opening between the abutments at Lines A and B. Increase in velocities in observed near the upstream abutment at Line C. The dike with a 15-degree angle produces slightly lower velocity along Lines A and B.

(3) Curved Dikes

The majority of tests were conducted with straight dikes to simplify the observations, while fully realizing that curved dikes would be more desirable in providing a more efficient velocity distribution and in preventing formations of eddies at the wall discontinuities. Some tests were carried out with curved dikes, and Fig. 9 shows that a very uniform velocity distribution may be obtained. The dike was tangent to the vertical wall abutment, and had a shape of a spiral. (Sketch D).

VI. PRELIMINARY ANALYSIS OF DATA

(A) 90° Approach

(a) Continuity equation.

For a rectangular channel, the continuity equation may be written as:

$$Q = V\,b\,y \qquad (1)$$

where: Q = discharge

V = velocity

b = width

y = depth

By taking the natural logarithm of equation (1)

$$\log_e Q = \log_e V + \log_e b + \log_e y \qquad (2)$$

and then, by differentiating Eq. (2) the following equation is obtained:

$$\frac{dQ}{Q} = \frac{dV}{V} + \frac{db}{b} + \frac{dy}{y} \qquad (3)$$

As the discharge is constant, the steady flow exists, and

$$\frac{dV}{V} + \frac{dy}{y} = -\frac{db}{b} \qquad (4)$$

Although in actual experiments, the velocity and depth were not constant in the opening across the abutments, sufficient data were taken to enable determination of average velocity and depth over Line B.

It was indicated in Sketch A that the effective width of the opening is reduced, and thus the efficiency of transmission of channel is decreased. When spur dikes are added, the effectiveness of the channel increases as the dikes guide the flow smoothly between the abutments.

Let us call the effective width of the channel without spur dikes b_o, and the effective width with spur dikes b. The difference between the two widths may be written as:

$$\Delta b = b - b_o = nb_o - b_o \qquad (5)$$

where n = measure of effectiveness of the channel

Equation (4) may also be written in a differential form:

$$\frac{\Delta V}{V_o} + \frac{\Delta y}{y_o} = - \frac{\Delta b}{b_o} \qquad (6)$$

where ΔV and Δy stand for conditions after and before installing spur dikes

subscript $_o$ = original conditions

Equation (6) may be written as:

$$\frac{\Delta V}{V_o} + \frac{\Delta y}{yo} = - \frac{(n-1)b_o}{b_o} = n - 1 \qquad (7)$$

or

$$n = 1 - \frac{\Delta V}{V} - \frac{\Delta y}{y} \qquad (8)$$

In the analysis, the differences in average velocity and depth were computed. Since in most cases the installation of spur dikes caused a decrease in average velocity and a decrease in depth (Fig.10), n was found to be greater than one, which indicates an increase in the efficiency of transmission of the channel. The values of n were plotted against percentage opening in Fig. 11, which indicates the following:

(1) For the openings tested, the dike placed at $\alpha = 20°$ yielded approximately similar increase in effectiveness.

(2) Doubling the length of dike showed only a small increase in value of n.

(3) While for small percentage openings the benefits appear to be independent of the angle and length, for large openings a dike placed at $\alpha = 20°$, provide a more efficient channel. In addition, very high velocities occur at the end of dike with $\alpha = 0$.

(b) Velocity Parameter

One of the useful parameters in this study was found to be $\left(\frac{V - V_s}{V}\right)^k = \left(\frac{\Delta V}{V}\right)^k$

where V = velocity in the channel
with no dikes employed
V_s = velocity in the channel
when dikes were used
k = exponent

It was found that useful plots may be obtained with value of $k = 1/2$, although other values could be used. Figures 12 and 13 present the plots of $\sqrt{\Delta V/V}$ (named the velocity parameter) versus percentage opening and dike angle respectively. It may be seen that:

(1) The effect of dike length (L_d) is unimportant for values between 18 inches and 36 inches. As the

openings between abutments (L_o) were 27-5/8 in., 41-7/8, and 52-1/2 in., the following L_d/L_o ratios: 0.652, 0.43, and 0.343 existed for L_d = 18 in.

(2) A dike with $\alpha = 0°$ has the greatest influence for 22.9% opening, while a dike with $\alpha = 10°$ has the greatest value for about 35% opening, and a dike with $\alpha = 20°$ for 43.6% opening. The average influence the angle α is also indicated in Fig. 11 and 12.

(B) 60° APPROACH

(a) Figures 14 and 15 present the plots of $\sqrt{\left|\frac{\Delta V}{V}\right|}$ versus percentage opening and dike angle, respectively. The plots were made for Line A, B, and C.

It may be seen that:

(1) At Line A, the spur dike is most effective at 50% opening.

(2) At centerline (Line B), the spur dike is most effective at between 30 and 35% opening, depending on the dike angle α.

(3) At Line C, the dike is most effective at the 22.9% opening.

(b) It was shown in Fig. 8 that using a spur dike at the downstream abutment improved conditions near the abutment, while actually increasing the velocities near the upstream abutment (on Line C). Pilot studies indicated that considerable improvement is obtained if a spur dike is also placed at the upstream abutment.

VII. CONCLUSIONS

1. Spur dikes decrease the depth of water through the constrictions.
2. Properly designed spur dikes guide flow in the opening between abutments, reducing the chance of scour at the abutments.
3. Spur dikes can produce uniform flow between abutments.
4. Length of dike greater than a minimum length is not important in producing a uniform velocity distribution between the abutments.
5. Shape of dike is of importance, the length of dike is that needed in development of that shape. The shape depends upon the flow and percentage opening. Various shapes may be used: logarithmic, spiral, involute, etc. The shape of dike should be determined for maximum flow expected. This will provide satisfactory conditions for lower flows.
6. Straight, stub-dikes should be used on the downstream side of the abutments to prevent scour at the abutment.

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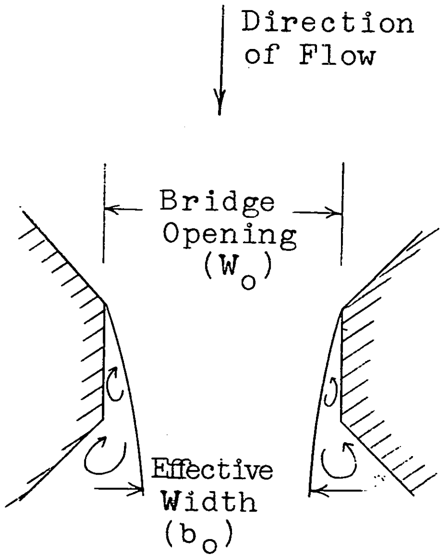
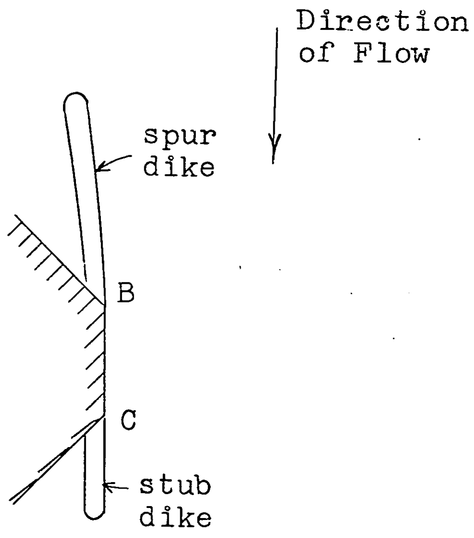
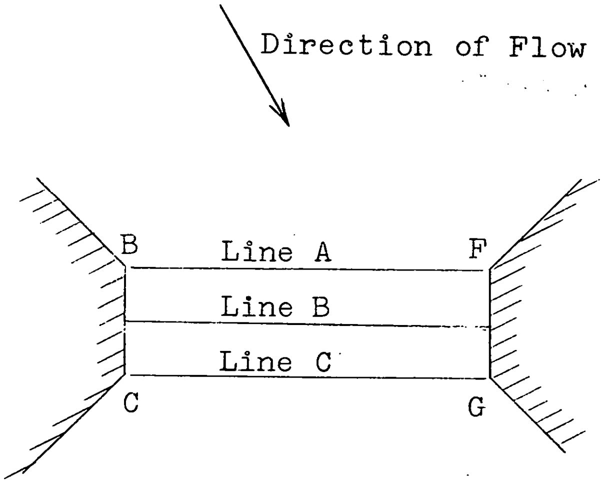


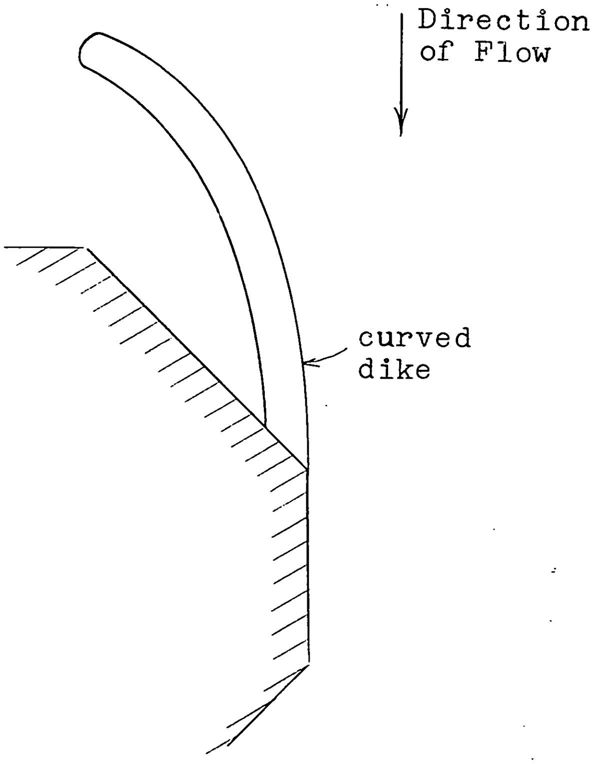
Sketch A



Sketch B



Sketch C



Sketch D

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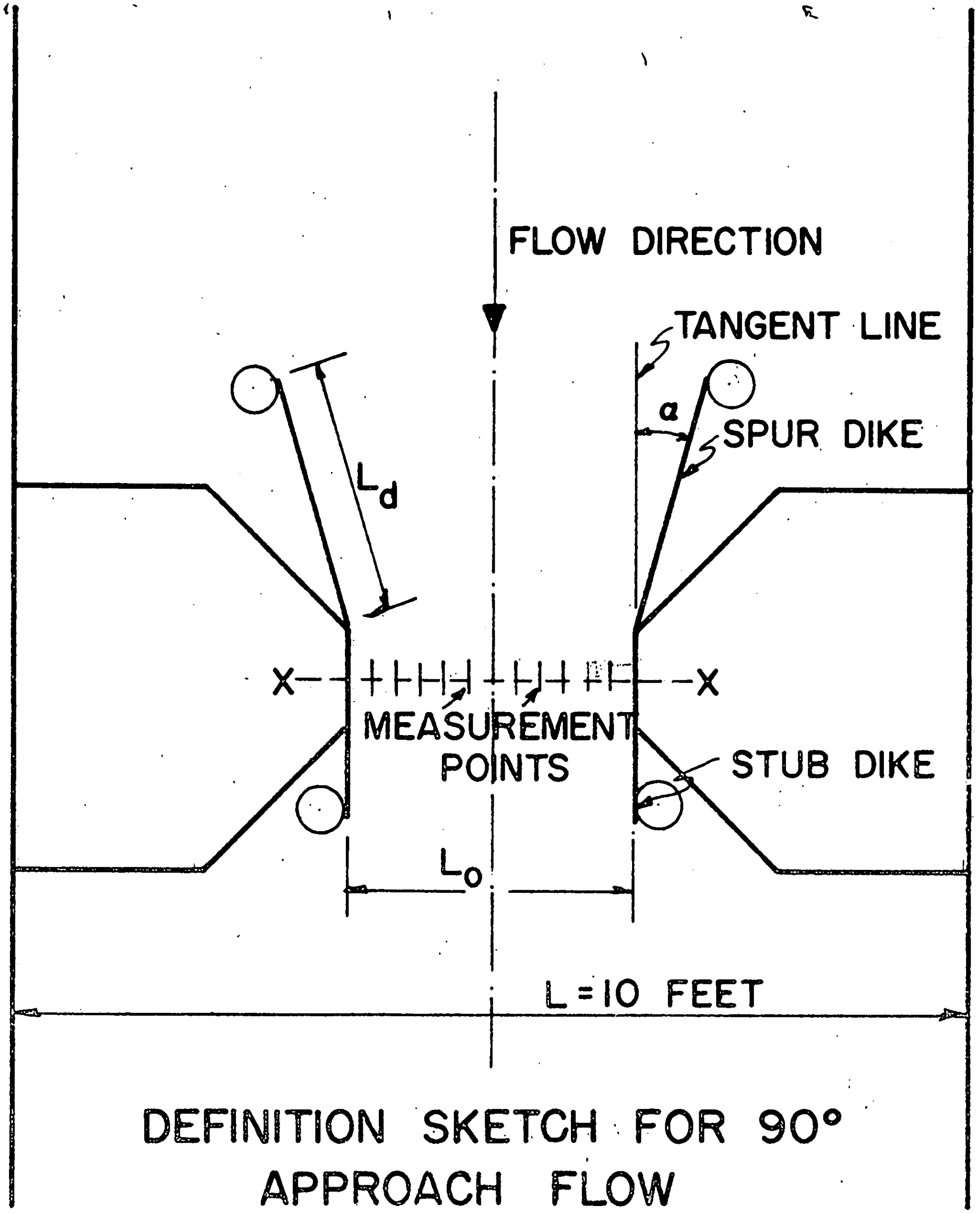
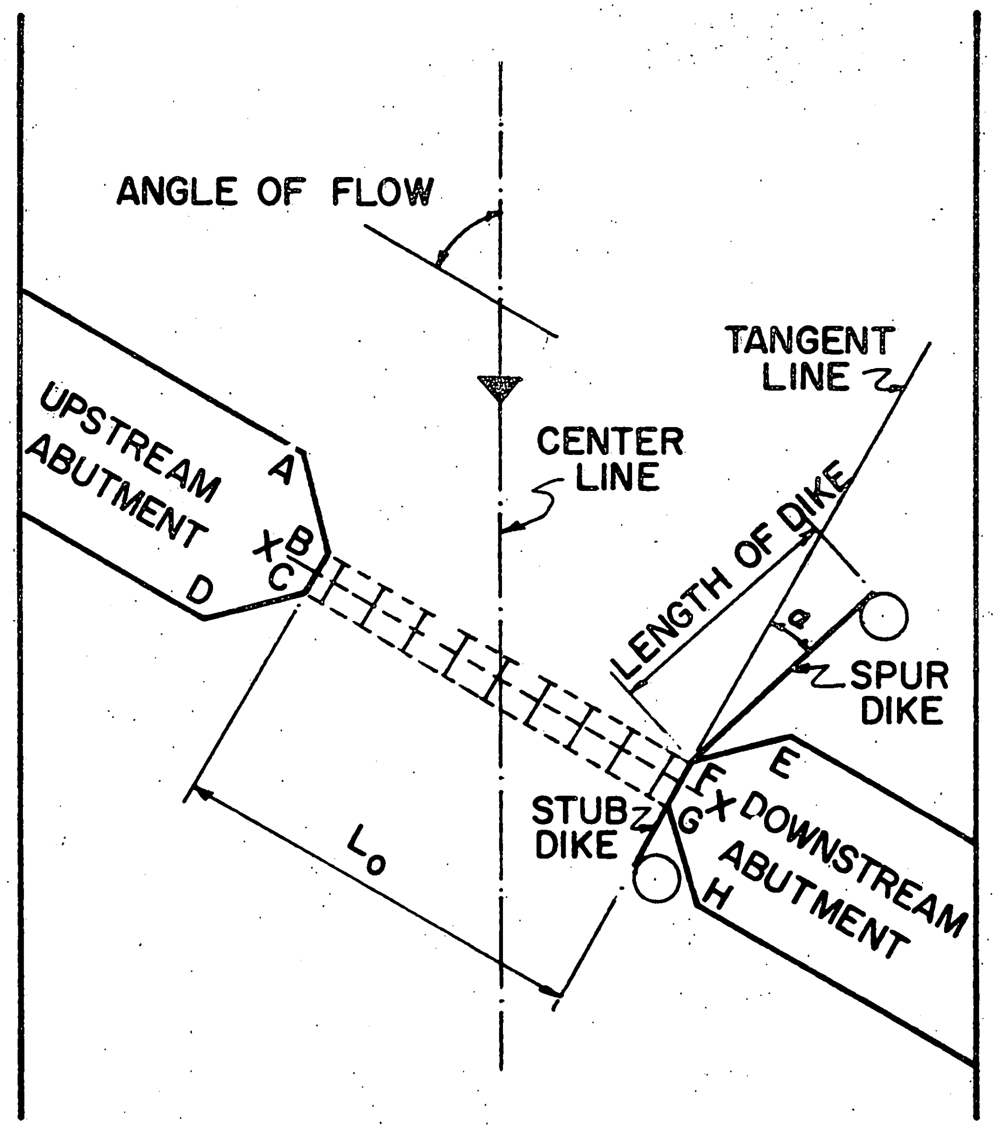


DEFINITION SKETCH FOR 90° APPROACH FLOW

FIG. 1



DEFINITION SKETCH FOR SKEWED ABUTMENT

FIG. 2

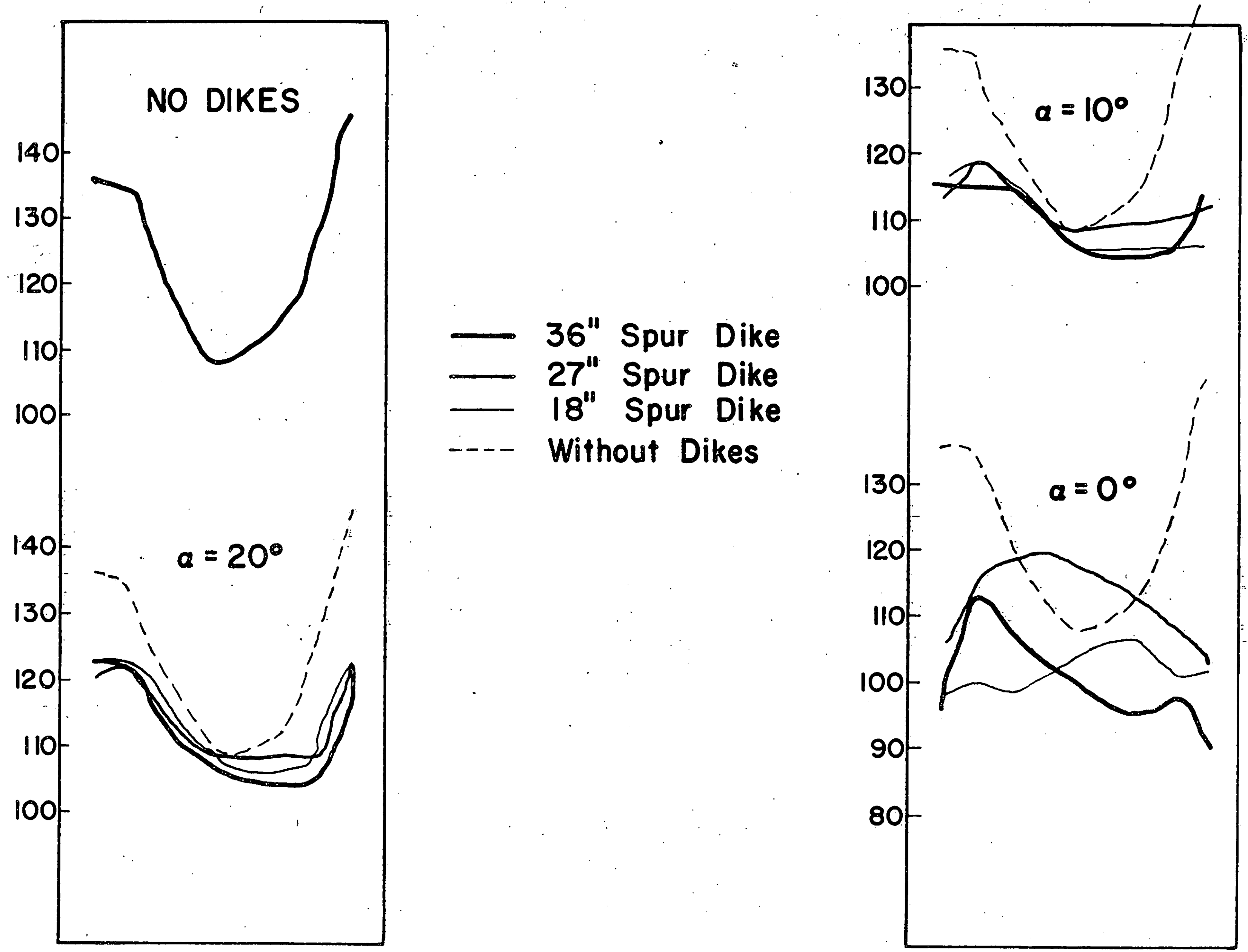


FIG. 3 VELOCITY DISTRIBUTION BETWEEN ABUTMENTS
90° APPROACH, DIKE ON DOWNSTREAM ABUTMENT, PERCENTAGE OPENING 22.9
DISCHARGE 2.92 cfs

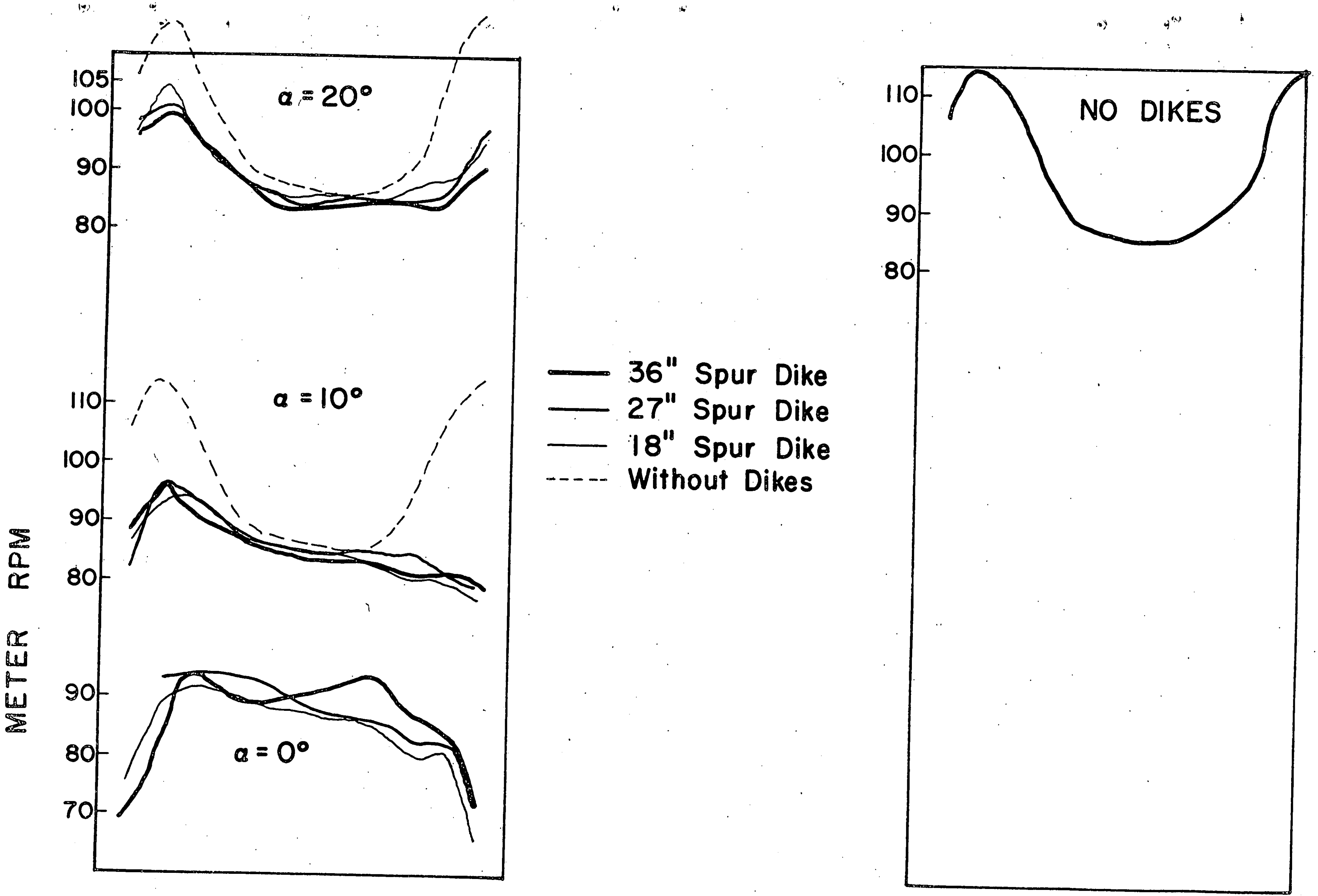


FIG. 4 VELOCITY DISTRIBUTION BETWEEN ABUTMENTS
90° APPROACH, DIKE ON DOWNSTREAM ABUTMENT, PERCENTAGE OPENING 34.9
DISCHARGE 2.92 cfs

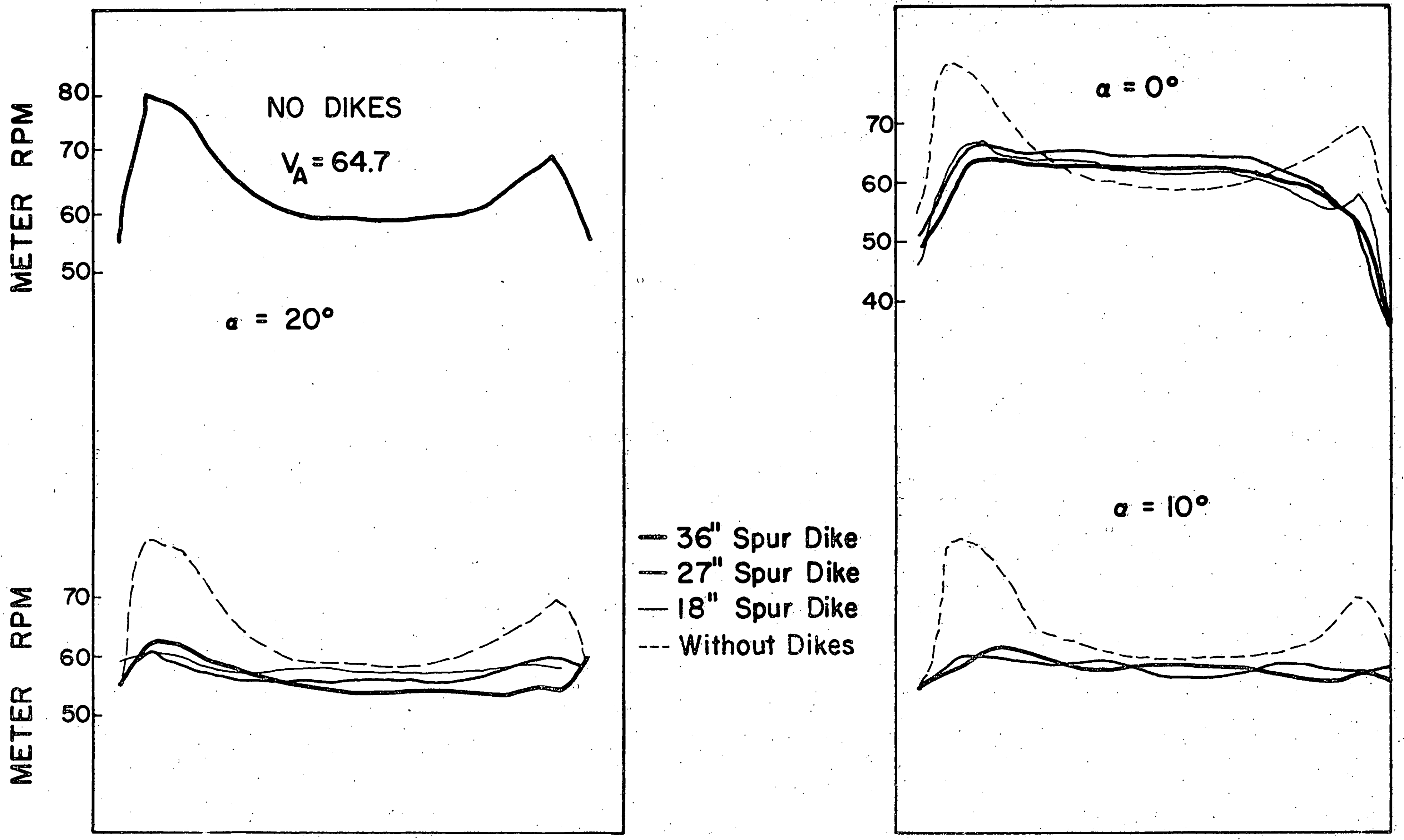


FIG. 5 VELOCITY DISTRIBUTION BETWEEN ABUTMENTS
90° APPROACH, DIKE ON DOWNSTREAM ABUTMENT, PERCENTAGE OPENING 43.8
DISCHARGE 2.92 cfs

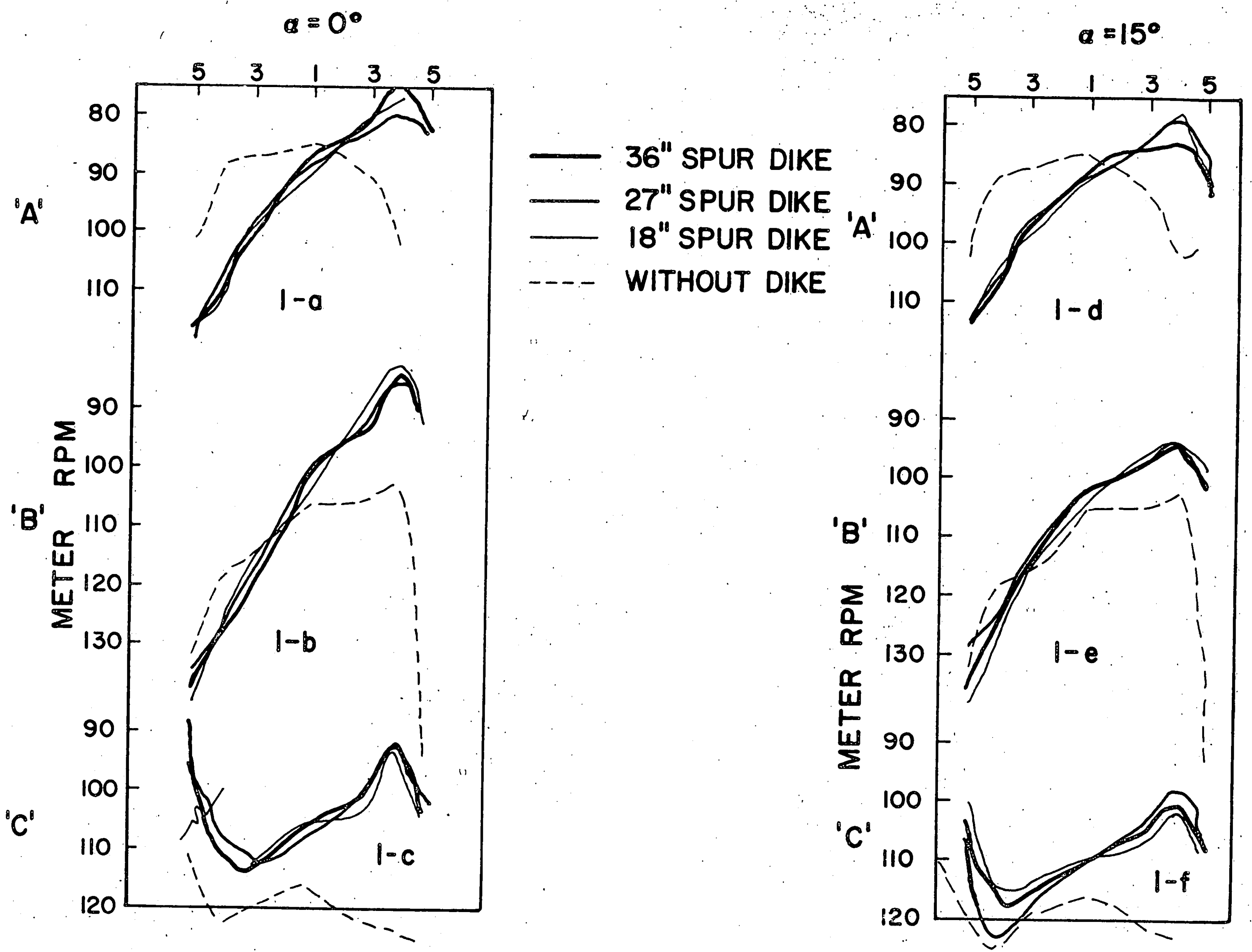


FIG. 6 VELOCITY DISTRIBUTION BETWEEN ABUTMENTS
60° APPROACH, DIKE ON DOWNSTREAM ABUTMENT, PERCENTAGE OPENING 22.9
DISCHARGE 2.92 cfs

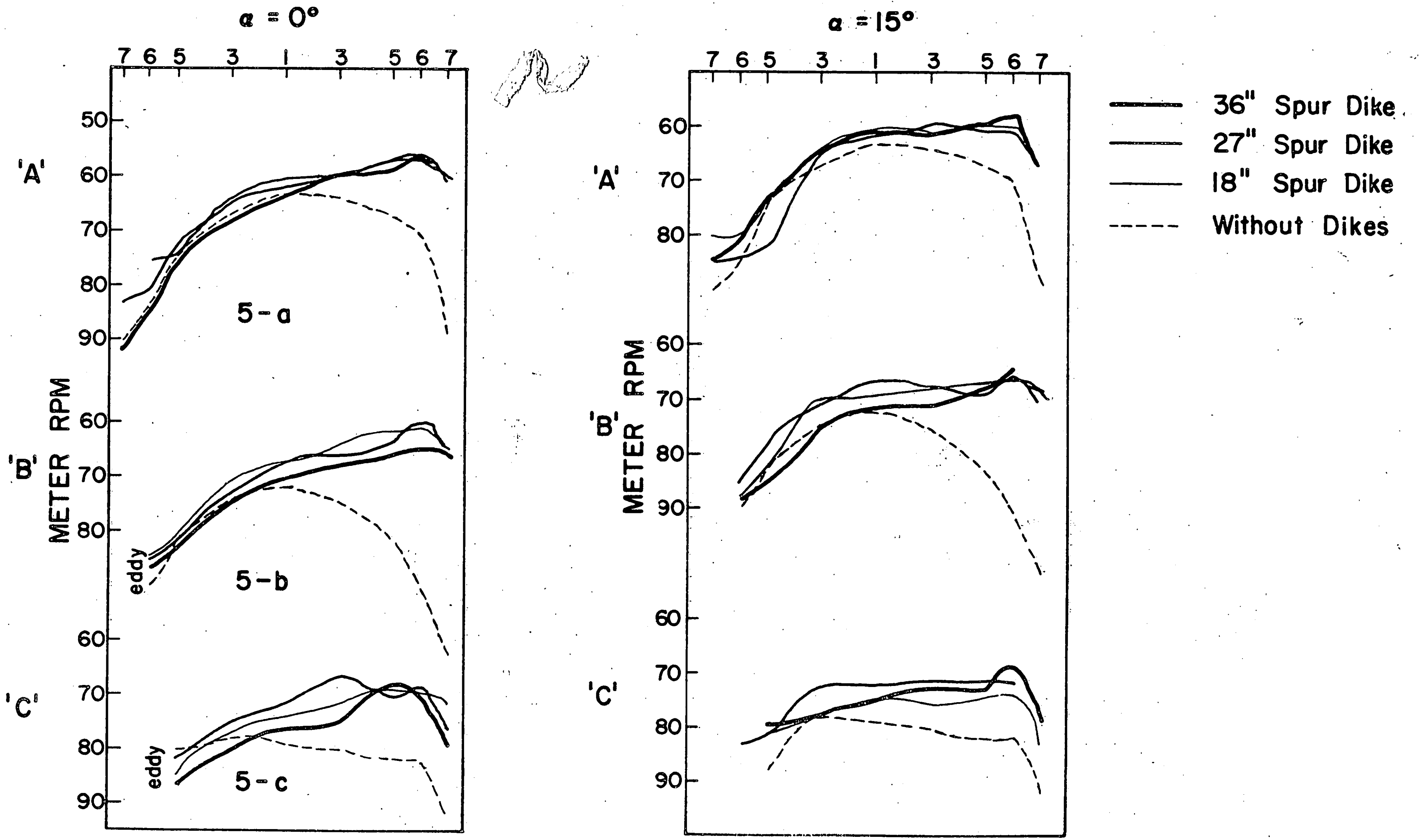


FIG. 7 VELOCITY DISTRIBUTION BETWEEN ABUTMENTS
60° APPROACH, DIKE ON DOWNSTREAM ABUTMENT, PERCENTAGE OPENING 34.6, DISCHARGE 2.92 cfs

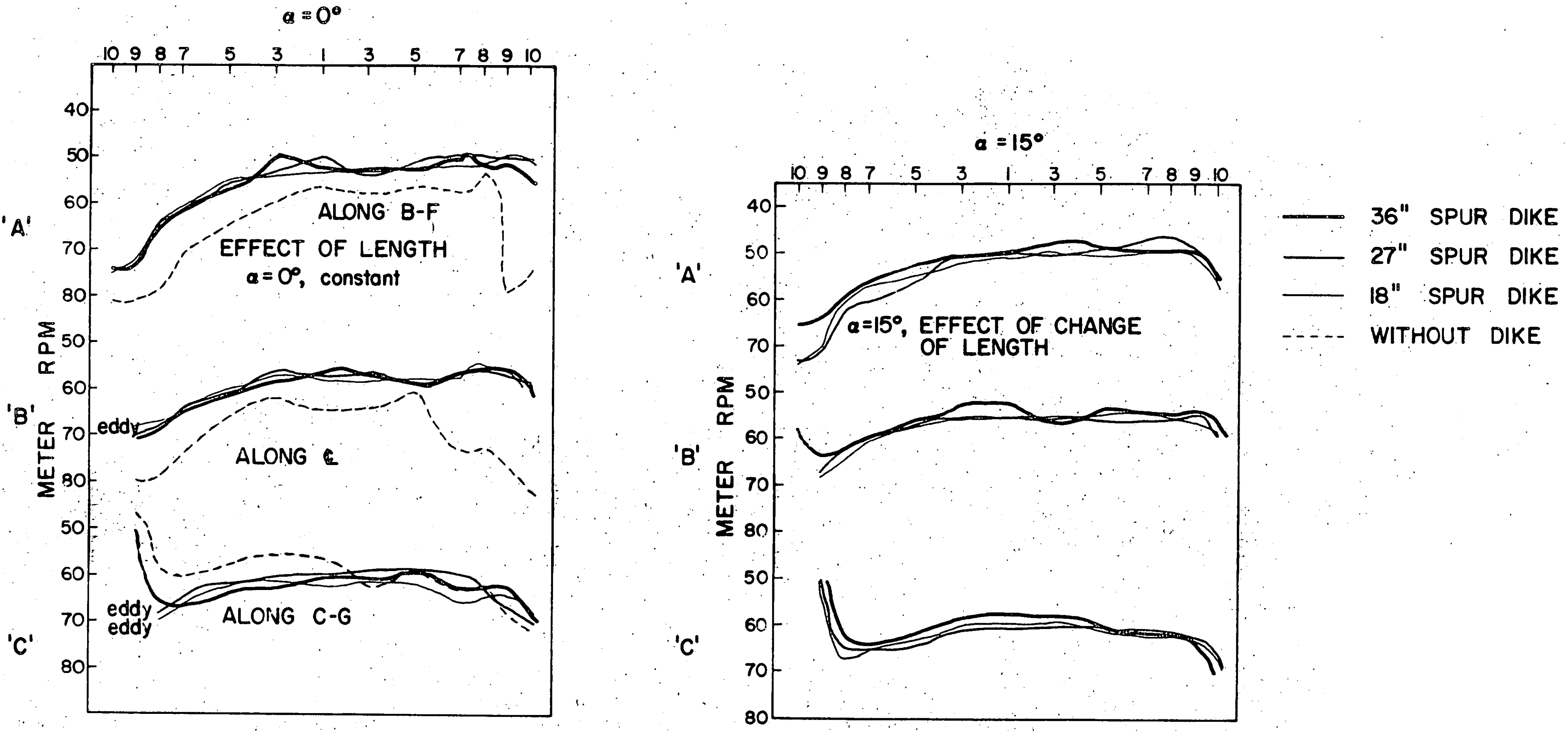


FIG. 8 VELOCITY DISTRIBUTION BETWEEN ABUTMENTS
60° APPROACH, DIKE ON DOWNSTREAM ABUTMENT, PERCENTAGE OPENING 49.6, DISCHARGE 2.92 cfs

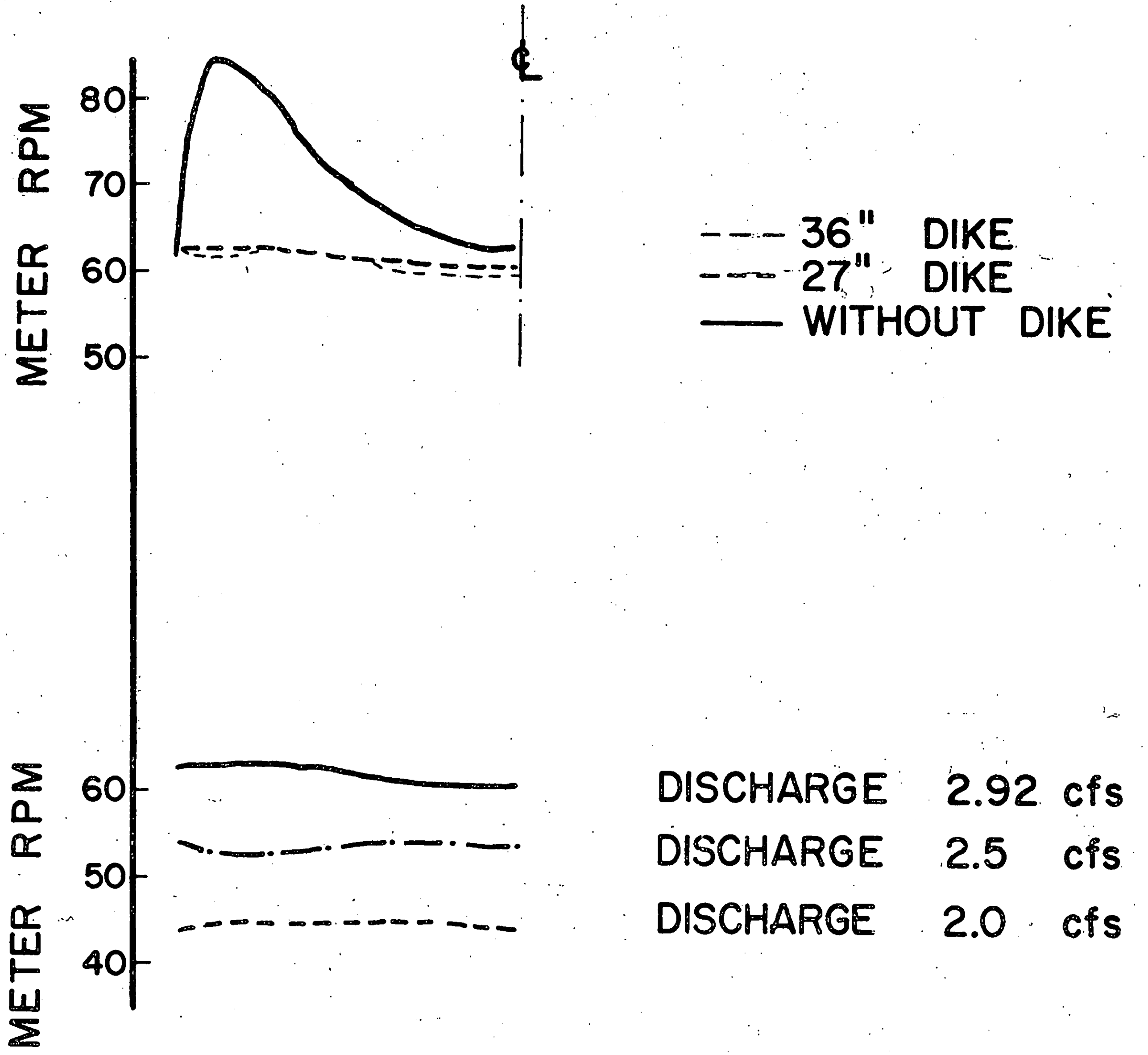


FIG. 9 VELOCITY DISTRIBUTION BETWEEN ABUTMENTS FOR CURVED DIKES. APPROACH 90°

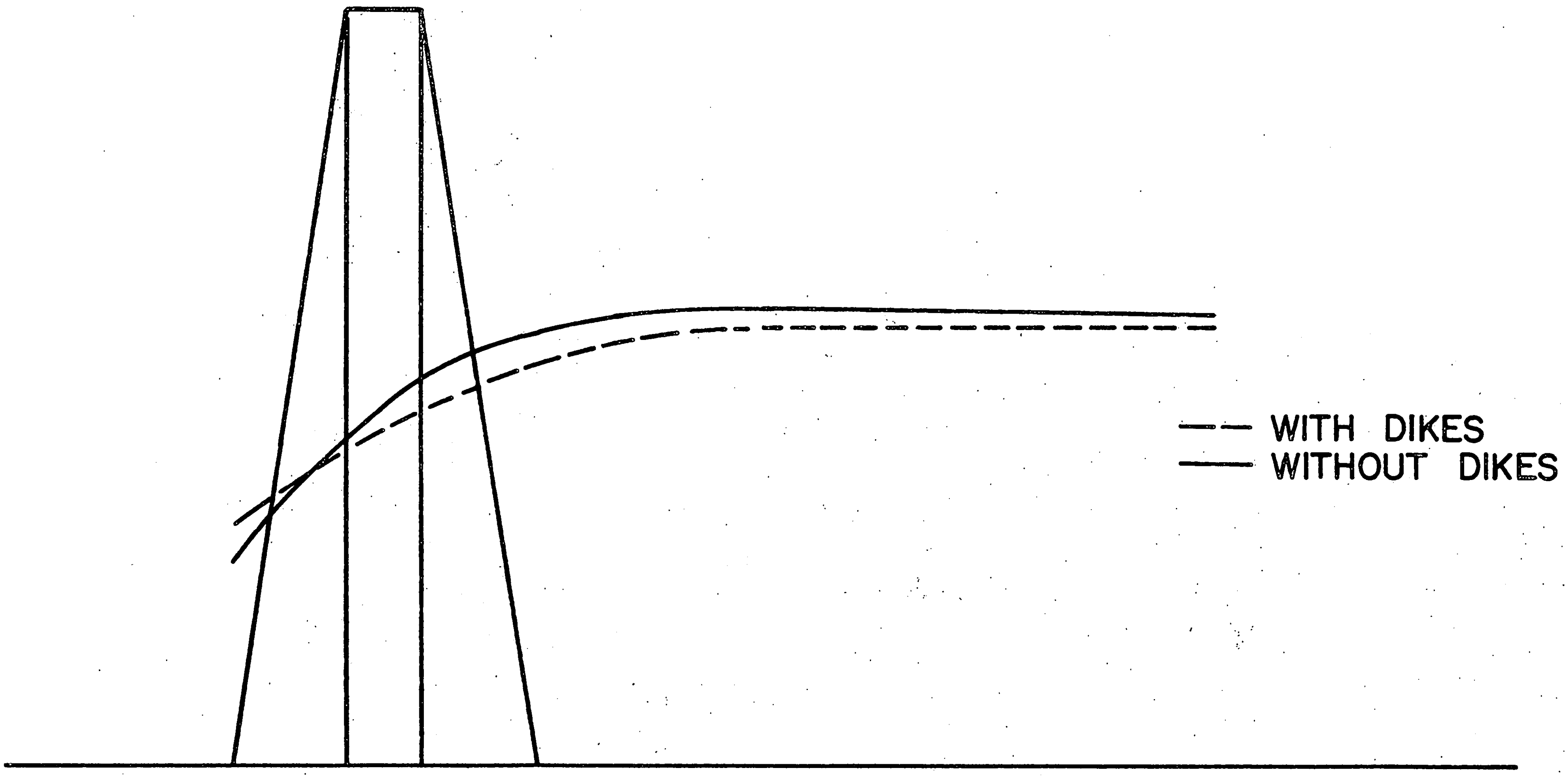


FIG. 10 THE EFFECT OF SPUR DIKES ON WATER SURFACE PROFILE ALONG CENTERLINE

PERCENTAGE OPENING 22.9 DISCHARGE 2.92 cfs

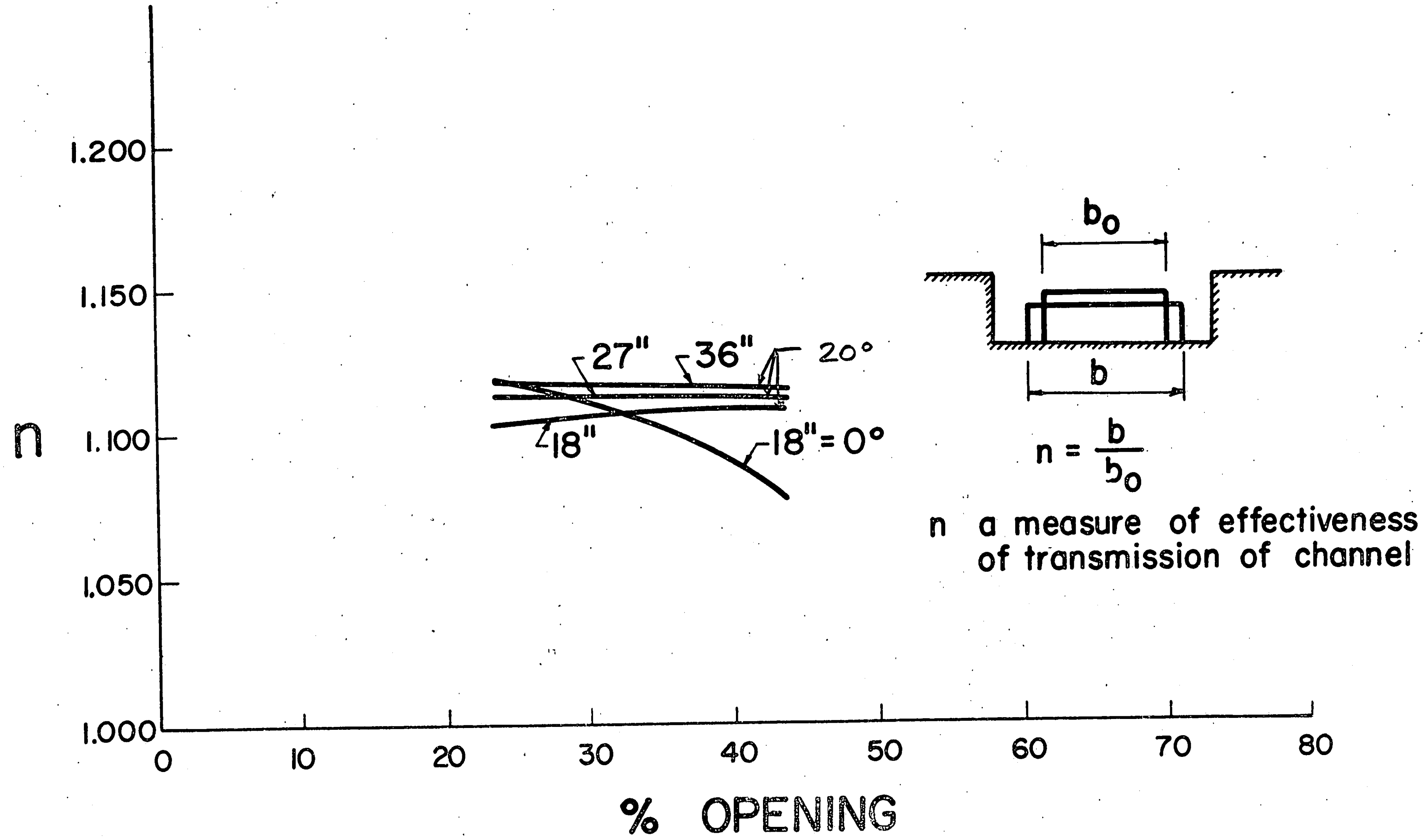


FIG. 11 INFLUENCE OF DIKES ON EFFECTIVENESS OF THE CHANNEL

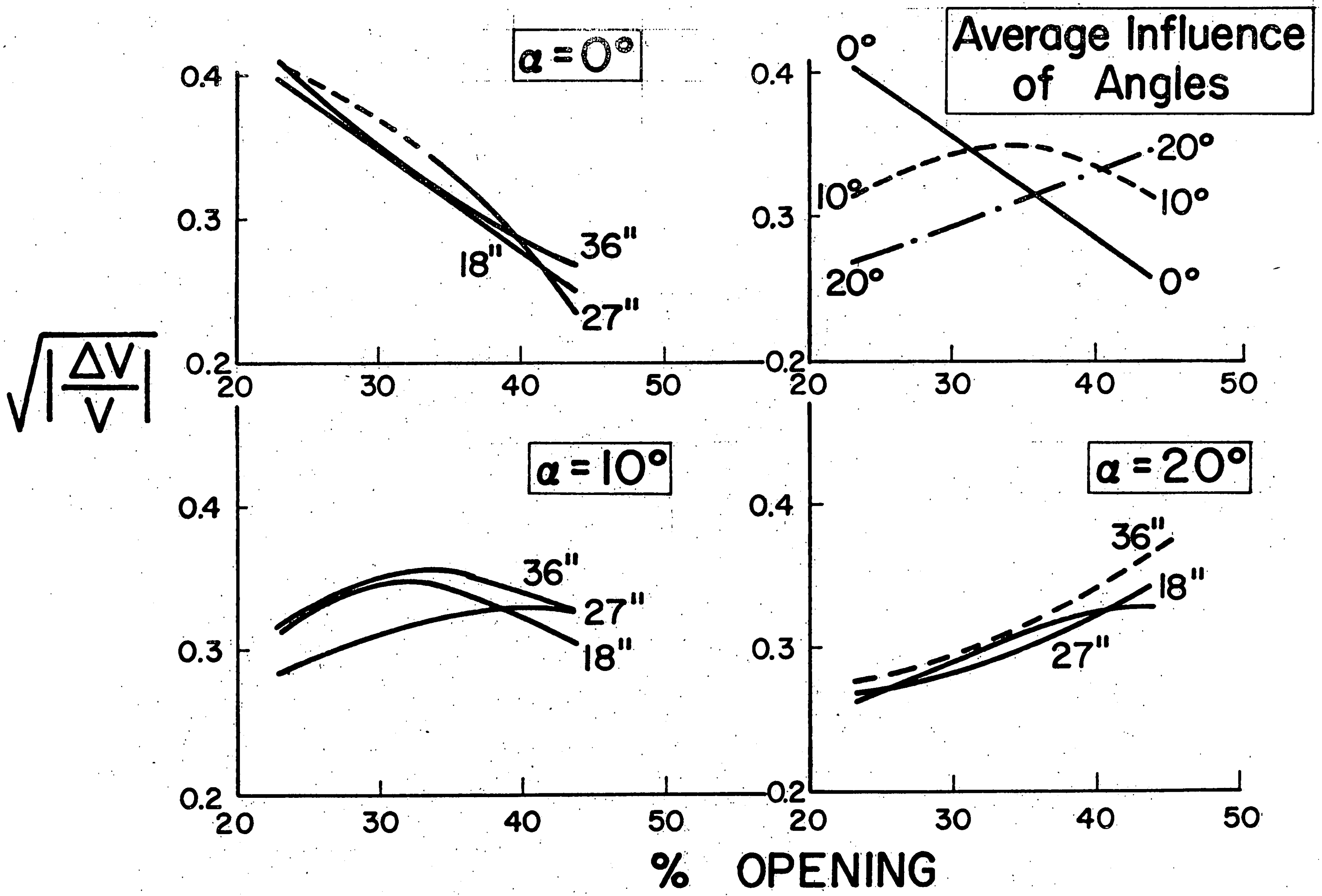


FIG. 12 EFFECT OF DIKE LENGTH ON VELOCITY PARAMETER FOR VARIOUS PERCENTAGE OPENINGS. 90° APPROACH, DISCHARGE 2.95 cfs

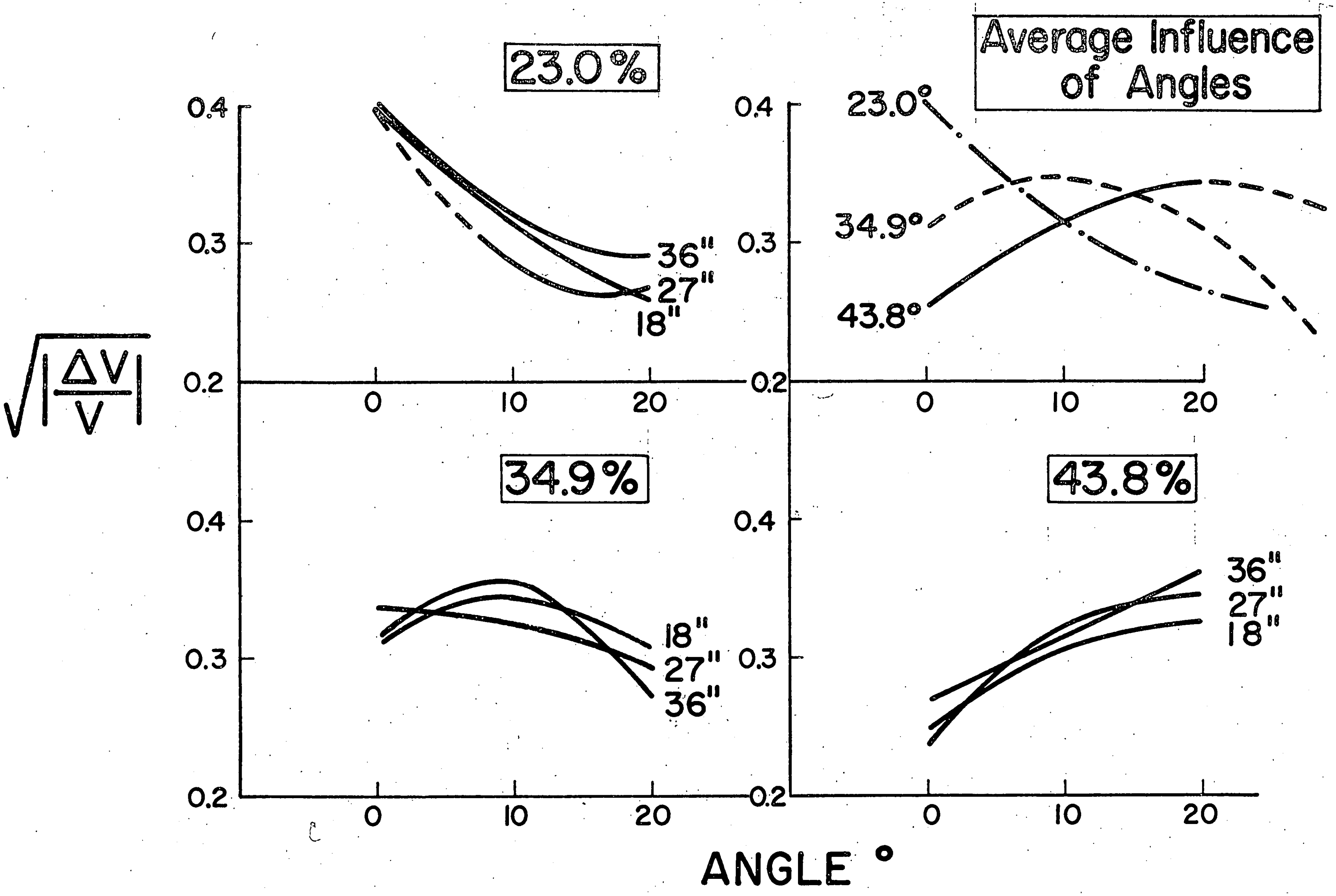


FIG. 13 EFFECT OF DIKE LENGTH ON VELOCITY PARAMETER FOR VARIOUS DIKE ANGLES. 90° APPROACH, DISCHARGE 2.92 cfs

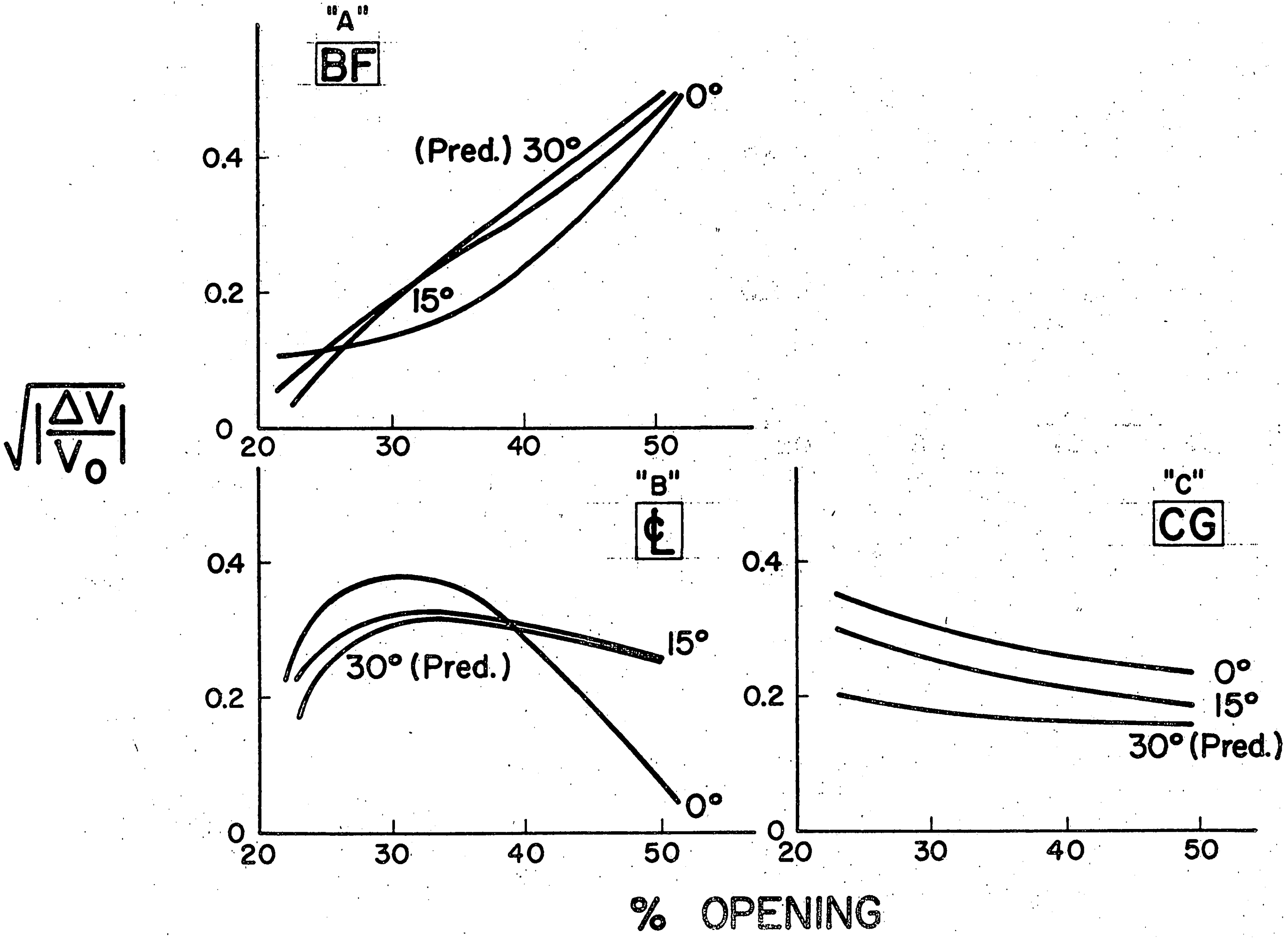


FIG. 14 EFFECT OF DIKE ANGLE AND LOCATION ON VELOCITY PARAMETER FOR VARIOUS PERCENTAGE OPENINGS. 60° APPROACH, DISCHARGE 2.9

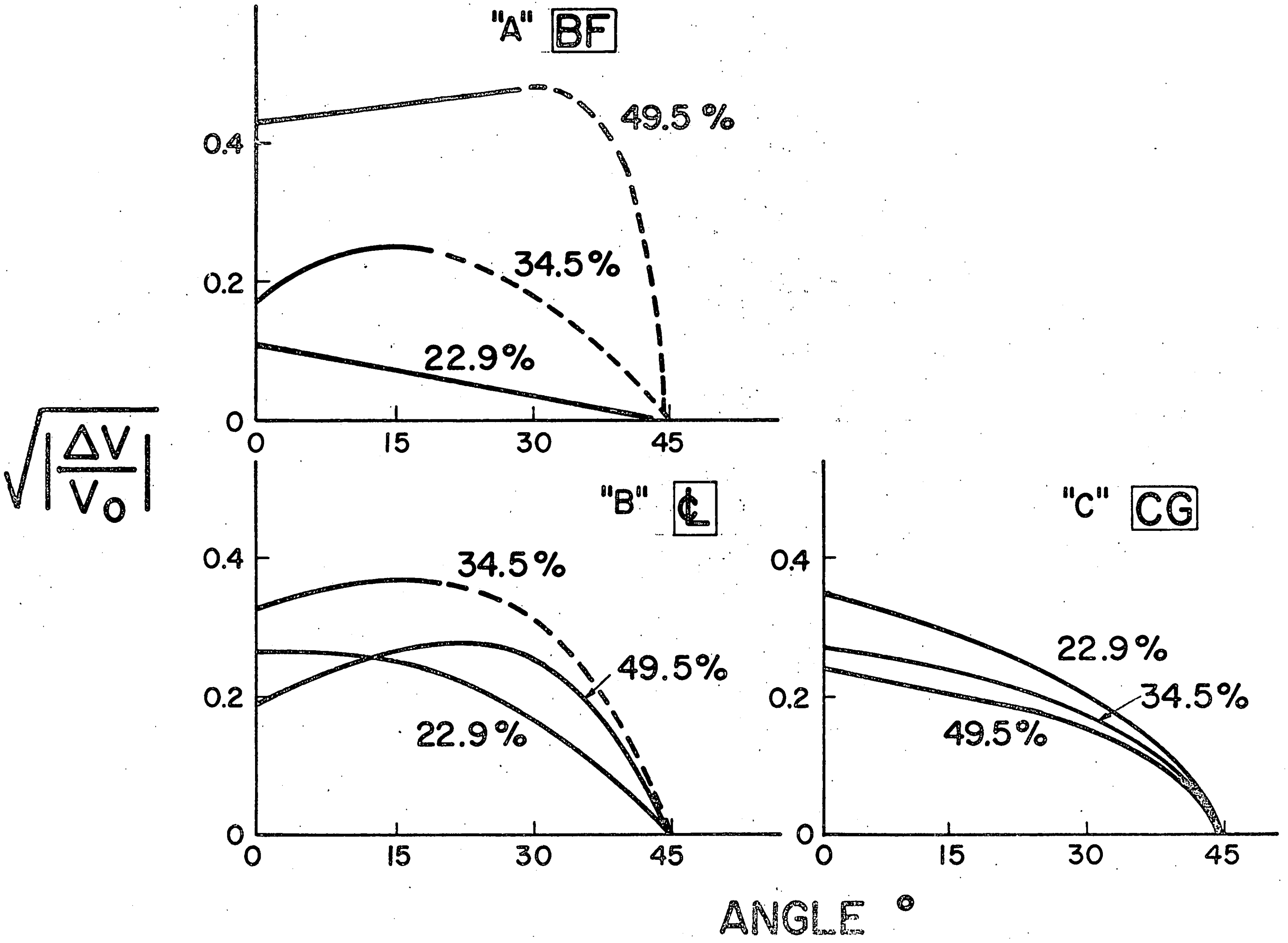


FIG. 15 EFFECT OF PERCENTAGE OPENING ON VELOCITY PARAMETER FOR VARIOUS DIKE ANGLES. 60° APPROACH, DISCHARGE 2.92 cfs

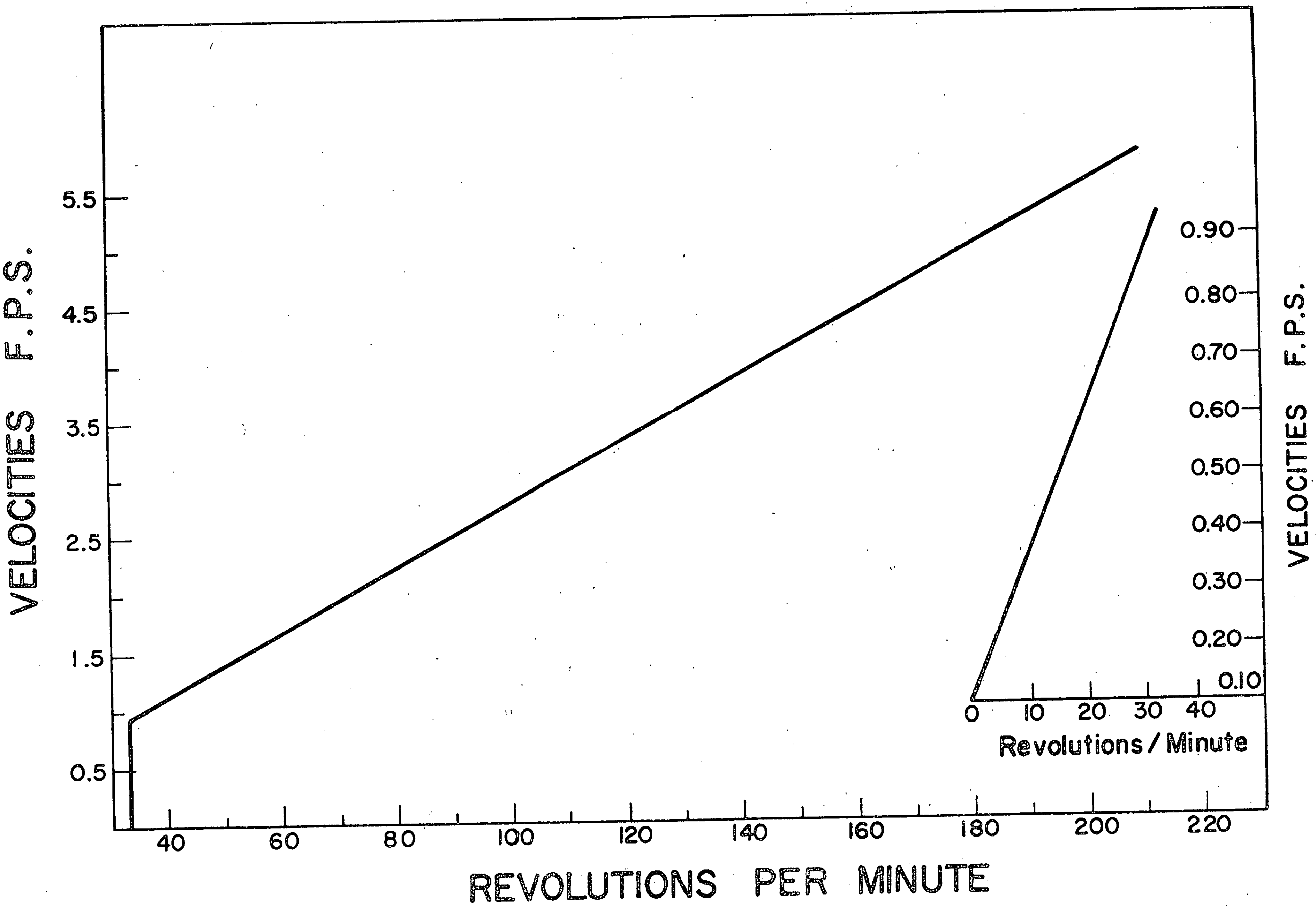


FIG. 16 OTT CURRENT METER CALIBRATION CHART