RESISTANCE TO FLOW IN PARTIALLY - COVERED CHANNELS

by

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I. INTRODUCTION

Recently, the need has been expressed for design information relating to the Flow Resistance of Partial Ice Covers on River Channels (Davar, 1979). Unfortunately, due to the dangers and difficulties involved in field studies, no information regarding this condition is currently available.

In order to gain some understanding of the resistance aspects of partial covers on channels, a laboratory study was conducted at the University of New Brunswick to determine the effects of various degrees of cover on the flow resistance in a rectangular channel; also, to compare these resistance effects with open channel flows for similar conditions.

The study was limited to five different cover conditions, with three flow depths and generally four average velocities for each depth. The openings were of fixed shape and arranged in a symmetrical pattern; the sizes of openings were varied to achieve the required percentage of cover.

The analysis of resistance phenomena was primarily based on the Manning's equation. The observed values of Manning's N obtained for the top cover, by considering a composite channel analysis, have been compared with predictions by various approaches proposed by Larsen, Hancu, Sabaneev and Chow.

Although this investigation cannot be strictly considered a model study of partial ice covers on natural streams, the results should provide guidelines for understanding flow resistance phenomena, and planning field studies.

II. EXPERIMENTAL APPROACH

The experiments described in this paper were conducted in a 12 m. long rectangular tilting flume [Fig. 1A], with various degrees of top cover. The cross-section of the flume was partitioned vertically to provide an effective width of 0.3048 m. [Fig. 1B].

A vertical baffle was installed at the head tank to dampen the disturbances generated at the entrance. Generally, uniform flow was maintained by adjusting the slope of the flume, and controlling a vertical tailgate. A sheet of expanded metal was placed on the flume bed to minimise the boundary effects of the sidewalls, and produce nearly two-dimensional flow. The top cover (except for the case of complete cover) was made up of a 9.5 mm. thick plywood stuck under a sheet of 51 mm. thick styrofoam.

Five different cover conditions were studied (0, 25, 50, 75 and 100%). For each of these covered conditions three flow depths (12.7, 19.05 and 25.4 cm.) were investigated; for each depth, generally, four average velocities ranging from 0.46 to 0.92 meters per second were examined. Figs. 2A, B and C, show the typical shape, size and arrangement of openings for parital cover conditions (25, 50 and 75% respectively).

In each experiment, the cover was fixed in place, and velocity profiles were measured on the centerline of a cross-section located at about the mid-length of the channel by means of a Nixon Model 403 probe (1.4 cm. propeller) and a Model 402 digital output indicator. In order to define the velocity profiles as accurately as possible, about 27 point measurements were obtained for each profile. A Marsh McBirney Model 201 M electromagnetic velocity meter was also used at a fixed location as a monitoring device to check the constancy of the flow.

As the flow regime changes from open to closed channel flow, a basic difficulty in definition of regimes arises. The uniform flow regime, defined as $S_b = S_w = S_e$, is strictly applicable to open channel conditions only; however, for closed conduit flow, the slope of the energy line (S_e) is independent of the slope of the conduit. For partially covered channels, the regime is an in-between condition. In these studies, for each case of partial cover, a "quasi-uniform flow" was maintained by making the slope of the energy line parallel to the bed (although the mean water surface was not parallel to the bed). This criterion was adopted to permit direct comparisons with corresponding open channel flow conditions. Admittedly, in nature, an alternative situation occurs in that the slope of the channel remains fixed for all flow conditions.

The slope of the flume was measured by a Wild N10 level; the slope of the energy line was computed from the head difference between two stations (located approximately 4.52 m. apart) measured by means of a pair of 7.62 cm. diameter stilling wells. An average of three measurements was used to define the slope of the energy line because of the effects of surging on the measurements of head loss.

III. ANALYTICAL APPROACH

III. 1. Analysis of Channel Resistance

The Manning Equation was adopted for analysis of flow resistance in channels (Chow, 1959). In S.I. units, the equation can be expressed as

$$V = \frac{1}{N} R^{2/3} S^{1/2} \; ; \qquad (1)$$

where V = mean velocity, R = hydraulic radius, S = slope of the energy line, N = resistance coefficient. The subscript o refers to open channel flows, and the subscript c indicates covered conditions.

For various covered conditions, including open, partial and complete cover, a tentative expression was used for the hydraulic radius. The expression adopted (for unit width analysis) was

$$R_c = \frac{A_c}{P_c} = \frac{Y_c \times 1}{(1 + \frac{P}{100})} \; ; \qquad (2)$$

where Y_c = total flow depth, P_c = effective wetted perimeter, and p = percentage of cover. The subscript c represents composite values.

The mean velocities of flow were obtained by integrating the measured velocity profiles. Using the measured slopes, mean velocities and the hydraulic radii defined by equation (2), the composite Manning coefficients (N_c) for various conditions (depths, velocities and degrees of cover) were computed from equation (1).

III. 2. Analysis of Composite Channel

For the composite analysis, each measured velocity profile was partitioned into the cover (top) and bed (bottom) zone, at the location of the maximum velocity (V_{max}) [Fig. 3]. The flow in each zone was assumed to be two-dimensional fully developed turbulent flow, and was considered to be governed by the corresponding boundary roughness. This approach was employed since the roughness of the bed remained relatively constant, while the roughness of the top cover varied greatly according to the degree of cover. The assumed 'constancy' of bed roughness for various flow conditions was mostly justified for the experimental conditions. Further, the analysis assumed that the average slope of the energy line was the same for the top and bottom zones, and for the entire section.

The basic equations for each zone are summarized below:

The Manning Equation

$$V_i = \frac{1}{N_i} R_i^{2/3} S^{1/2} ; \qquad (3)$$

The Hydraulic Radii (per unit channel width)

$$R_1 = \frac{A_1}{P_1} = Y_1 \text{ (bottom zone)} \qquad (4)$$

$$R_2 = \frac{A_2}{P_2} = \frac{Y_2}{(\frac{P}{100})} \text{ (top zone)}. \qquad (5)$$

The subscripts $i = 1$ and 2 were used to denote the bottom and top zone respectively. The mean velocity of each zone was obtained by integrating the velocity profile from the corresponding boundary to the location of maximum velocity (V_{max}).

In using these equations, it has to be remembered that as pointed out by Pratte (1979), the Manning coefficient for each zone (N_1 and N_2) is fairly sensitive to the location of maximum velocity in the flat portion of the velocity profile. Thus, the identification of the location of the maximum velocity has to be done with great care.

III. 3. Velocity Distribution

According to the Karman-Prandtl theory for fully developed turbulent flow (rough boundary), the logarithmic velocity equation (Streeter, 1961) can be written as

$$\frac{v}{V_*} = A \ln \frac{y}{k'} + C ; \qquad (6)$$

where v = local velocity at a distance y from the rough boundary, $V_* = \sqrt{\frac{\tau_o}{\rho}}$ = shear velocity, τ_o = wall shear stress, ρ = mass density of fluid, $A = \frac{1}{\chi}$ and χ is the von-Karman turbulence constant, k' = roughness parameter, and C = a constant. Generally, $\chi = 0.40$ and $C = 8.5$ for normal rough boundary conditions. However, Bayazit (1975) pointed out that the constants χ and C varied with the 'relative submergence' (ratio of the open channel flow depth and the hemisphere radius (absolute roughness)). Sayre and Albertson (1961) have also pointed out that χ could range from 0.32 to 0.42, based on the analysis of Nikuradse's data by Vanoni.

The 'constant' C has been shown to vary with roughness shape, size and arrangement (Daily and Harleman, 1966); also with the shape of channel cross-section (Hey, 1979). The roughness parameter (k') is usually replaced by the equivalent sand-grain roughness (k_s), and depends on the roughness geometry, height and distribution of the boundary roughnesses.

Based on the study of flow resistance under a rough top boundary with large strip roughnesses, Ismail (1978) indicated that the shear velocity, V_*, varied locally with boundary conditions.

These aspects of V_*, A and C must be remembered in any attempt to estimate the apparent roughness height (k) from measured velocity profiles.

III. 4. Roughness from Velocity Profile

Attempts to estimate the apparent boundary roughness, k, for each zone from the measured velocity profiles (assuming logarithmic velocity distribution) as proposed by Larsen and presented by Pratte (1979) [Fig. 4] have not been encouraging, so far. The equation stated by Pratte to estimate the boundary roughness for each zone can be written as

$$k_i = C' \, Y_i \, e^{-a_i} \quad ; \tag{7}$$

in which, $a_i = \dfrac{V_{max}}{V_{max} - V_i}$.

Here, Y_i = flow depth from either boundary to the location of maximum velocity, and C' = a constant, having a value of 30 based on the Karman-Prandtl velocity distribution with $C = 8.5$ and $\chi = 0.40$.

From the plots of velocity profiles, deviations of measured velocity distributions from the logarithmic law were observed near the maximum velocity. Such deviations have also been pointed out by Hirayama (1981) and Lau (1982).

In most cases, for the top zone with partial covers, estimates of k turned out to be nearly equal the depth of the zone, rather unrealistic results. Perhaps, the difference between the measured and predicted velocity distributions near V_{max}, together with the variation of the constants χ and C may explain the unrealistic values of k obtained by equation (7).

III. 5. Composite Resistance Formulas for Ice-Covered Channels

It is essential to identify specifically the values of N_2 for the top cover to understand its variation with different degrees of cover. This is possible by analysis of the composite channel, as described in Section III. 2.

Among the numerous approaches, the methods proposed by Hancu, Chow, Sabaneev and Larsen were selected for comparisons. Uzuner (1975) has presented a comprehensive summary of these methods.

Using the Chezy-Manning equation, and assuming $V_c = V_1 = V_2$ (mean velocity for the composite section, and each zone), Sabaneev derived the following expression:

$$\frac{N_c}{N_1} = \left[\frac{1 + a\left(\frac{N_2}{N_1}\right)^{3/2}}{1 + a}\right]^{2/3} \tag{8}$$

in which, $a = \frac{P_2}{P_1}$.

Using the Manning and Darcy-Weisbach equations, and relating the boundary shear stresses (top and bottom) to the average shear stress, Hancu derived the following expression:

$$\frac{N_c}{N_1} = \frac{1}{\sqrt{2}}\left(\frac{R_c}{R_1}\right)^{1/6}\left[\left(\frac{V_1}{V_c}\right)^2 + \left(\frac{N_2}{N_1}\right)^2\left(\frac{R_1}{R_2}\right)^{1/3}\left(\frac{V_2}{V_c}\right)^2\right]^{1/2} \tag{9}$$

Based on the balance of shear forces, and using the Chezy-Manning equation, Chow developed the following relation:

$$\frac{N_c}{N_1} = \frac{1}{\sqrt{1 + a}}\left(\frac{N_2}{N_1}\right)\left[a^{3/4} + \left(\frac{N_1}{N_2}\right)^{3/2}\right]^{2/3} \tag{10}$$

Based on the Continuity and Manning equations, and assuming a wide rectangular channel (so that $R_i = Y_i$, $i = 1, 2$), Larsen derived the following equation:

$$\frac{N_c}{N_1} = \frac{0.63\left(\frac{Y_2}{Y_1} + 1\right)^{5/3}}{\frac{N_1}{N_2}\left(\frac{Y_2}{Y_1}\right)^{5/3} + 1} \tag{11}$$

However, the assumption of $R_2 = Y_2$ (top zone) is not valid for partially covered channels. The modified Larsen equation, which applies to different covered conditions, can be written as:

$$\frac{N_c}{N_1} = \frac{\frac{Y_c}{Y_1}\left(\frac{R_c}{R_1}\right)^{2/3}}{1 + \frac{Y_2}{Y_1}\left(\frac{R_2}{R_1}\right)^{2/3}\left(\frac{N_1}{N_2}\right)} \qquad (12)$$

An alternative form of this equation, using the percent cover parameter, is:

$$\frac{N_c}{N_1} = \frac{\left(\frac{Y_c}{Y_1}\right)^{5/3}\left(1 + \frac{P}{100}\right)^{-2/3}}{1 + \left(\frac{Y_2}{Y_1}\right)^{5/3}\left(\frac{P}{100}\right)^{-2/3}\left(\frac{N_1}{N_2}\right)} \qquad (13)$$

All the above equations are applicable to different covered conditions (partial or complete) by adjusting either the wetted perimeter or hydraulic radius of each zone, and of the entire section (if required). For the estimation of Manning's coefficient for the top zone (N_2), equations (8), (9), (10) and (13) are rearranged, and summarized as follows:

Sabaneev: $$N_2 = N_1\left[\frac{\left(\frac{N_c}{N_1}\right)^{3/2}(1 + a) - 1}{a}\right]^{2/3} \qquad (14)$$

Hancu : $$N_2 = N_1\left[\frac{2\left(\frac{N_c}{N_1}\right)^2\left(\frac{R_c}{R_1}\right)^{-1/3} - \left(\frac{V_1}{V_c}\right)^2}{\left(\frac{R_1}{R_2}\right)^{1/3}\left(\frac{V_2}{V_c}\right)^2}\right]^{1/2} \qquad (15)$$

Chow : $$N_2 = \left[\frac{\left(N_c\sqrt{1 + a}\right)^{3/2} - N_1^{3/2}}{a^{3/4}}\right]^{2/3} \qquad (16)$$

Larsen : $$N_2 = N_1\left[\frac{\left(\frac{Y_2}{Y_1}\right)^{5/3}\left(\frac{P}{100}\right)^{-2/3}}{\left(\frac{Y_c}{Y_1}\right)^{5/3}\left(1 + \frac{P}{100}\right)^{-2/3}\left(\frac{N_1}{N_c}\right) - 1}\right] \qquad (17)$$

It may be recalled that $a = \frac{P_2}{P_1}$ in the above equations.

IV. PRESENTATION OF RESULTS

Results showing the effects of different degrees of cover, varying depths, and velocities on the resistance characteristics for open and covered conditions, are discussed in this section. Also, the influence of these parameters on the location of maximum velocity is presented. Preliminary deductions are also drawn from the results presented. It should be noted that in each dimensionless plot in Fig. 5 to 8, the characteristic upper and lower velocity curves are shown only.

IV. 1. Open Channel Resistance Characteristics

Examination of the values of N_o, for three depths, and about four velocities, showed that they were relatively invariant. N_o was found to be 0.0227, 0.0229 and 0.023, for depths equal to 12.7 cm., 19.05 cm., and 25.4 cm., respectively. As generally assumed by various authors (Pratte, 1979), these values of N_o were considered to be constant for the corresponding depths; that is, unaffected by variations of velocity.

IV. 2. Covered Channel Resistance Characteristics

IV. 2.1 Comparisons of bed resistance for covered and open conditions

Fig. 5 shows the plots of $\frac{N_1}{N_o}$ vs. % Cover (p) for different depths and velocities (characteristic upper and lower). For the experimental range of data, the assumption of 'constancy' of the bed resistance coefficient ($N_o = N_1$), for corresponding depths, was generally valid within a deviation of ± 10%; but for the higher velocities in the 50% to 75% range of cover, a maximum deviation up to 40% was noted. The difference between N_o and N_1 for the covered conditions is probably due to: i) the possible transfer of eddies from the top to the bottom zone; ii) sensitivity to the location of maximum velocity. Also, there seemed to be a slight increase of the ratio $\frac{N_1}{N_o}$ for increasing velocities, in the case of each depth.

IV. 2.2 Variation of composite resistance

The maximum variation of N_c with respect to N_o was found to occur between 25% and 55% cover, for all depths and velocities as shown in Fig. 6. It was also observed that the maximum and minimum values of the ratio $\frac{N_c}{N_o}$ for the corresponding characteristic upper and lower velocities occurred for the depth of 19.05 cm.. The $\frac{N_c}{N_o}$ tended to increase and shift laterally to the right, as velocities increased, for each depth. The maximum observed value of $\frac{N_c}{N_o} \cong 1.85$; it occurred for the depth of 19.05 cm. and the characteristic curve for the higher velocity. For complete cover conditions, the effects of depth and velocity on the variation of the composite resistance coefficient N_c was negligible (N_c was about 80% of N_o).

IV. 2.3. Variation of cover resistance

The observed N_2 values were obtained by analysis of a composite channel; this was done by partitioning the channel at the location of maximum velocity into a cover (top) and bed (bottom) zone. The values of N_2 were computed by applying Manning's equation to the top zone. The results are presented in Fig. 7 in full lines.

The general behaviour of plots of $\frac{N_2}{N_o}$ vs. p [Fig. 7] is similar to the plots of $\frac{N_c}{N_o}$ vs. p [Fig. 6]. However, the specific variations in the cover resistance coefficients, N_2, are seen directly in Fig. 7. The peak values of $\frac{N_2}{N_o}$ occurred in the range of 25% to 40% cover, for all depths and velocities.

For the experimental conditions, a maximum value of $\frac{N_2}{N_o}$ equal to 3.2 was attained in the range of 30% to 40% for p (cover) for the upper characteristic velocities. With N_o equal to 0.023 (approximately for all three depths), this indicated a maximum value of N_2 approximately equal to 0.074. This value may be considered to be equivalent to that for fragmented ice covers (unconsolidated ice jams) in natural streams.

A comparison of the observed values of N_2 with those predicted by alternative analytical approaches based on Larsen, Hancu, Sabaneev and Chow indicated that the methods proposed by Larsen and Sabaneev gave results relatively closer to the observed values than the other methods. The maximum overestimation due to these methods compared to the observed peak values of $\frac{N_2}{N_o}$ was approximately 6% (Sabaneev and Larsen); the difference in location between the observed and predicted positions (on the p axis) of the peak values of $\frac{N_2}{N_o}$ was within ±10%. The methods of Hancu and Chow tended to underestimate the peak values of $\frac{N_2}{N_o}$ by as much as 30%. In these cases, also the difference in location of peak values were within ±10% on the p axis.

IV. 3. Characteristics of Velocity Distribution

IV. 3.1 Location of maximum velocity

It has been reported in literature that the position of maximum velocity is sensitive to the relative magnitudes of N_2 and N_1. Therefore, the measured velocity profiles have been examined regarding this aspect, and the results are shown plotted in Fig. 8 for the three depths.

The curves presented should be considered as representative trends in the data, as there was considerable scatter in the points.

As may be expected, the greater resistance due to partial cover resulted in the depression of the location of maximum velocity from the top boundary; the curves generally were trough shaped.

For open channel conditions (p = 0%), the effect of variation in depth on the location of maximum velocity for each velocity was not significant; the spread between the higher and lower velocities was largest for the largest depth.

For complete covered conditions (p = 100%), the effect of velocities on the location of maximum velocity was negligible; however, there was a slight depression in the position of maximum velocity for the largest depth. Perhaps, this was related to the increases sidewall effects for greater depths for the narrow experimental channel.

The lowest portion of the troughs in Fig. 8 were located in the range of 30% to 55% cover. It may be recalled that this was approximately the same range for the peak values of $\frac{N_2}{N_o}$ and $\frac{N_c}{N_o}$. There was a tendency for the lower portion of the troughs of each curve to drop down, and shift laterally to the right with increasing velocity.

IV. 3.2 Deviation from the logarithmic distribution

It has been reported in literature (Lau, 1982 and Hirayama, 1981) that for channels with a rough cover, the normal logarithmic distribution of velocities deviates from the theoretical predictions, the observed values being less than the theoretical predictions. Examination of the measured velocity profiles for this study has confirmed such deviations as summarised below in Table 1.

TABLE 1.

% Cover	Depth below V_{max} (% of Y_1)	Deviation from V_{max} (%)
25	up to 25	up to -7
50	up to 45	up to -10
75	up to 25	up to -5
100	up to 25	up to -10

Table 1 indicated that, in some cases, particularly in the bottom zone of the composite section, the velocity profiles were logarithmic only for 55% of the flow depth of each zone. The measured maximum velocities were approximately 10% less than those predicted by the logarithmic-law.

V. CONCLUSIONS AND RECOMMENDATIONS

The effects of different degrees of cover (0, 25, 50, 75 and 100%) on the resistance coefficients (N_1, N_2 and N_c) have been examined for three depths (12.7, 19.05 and 25.4 cm), and about four velocities (ranging from 0.46 to 0.92 m/s) for each depth. Based on these studies, the following conclusions have been drawn:

1. The Resistance Coefficient N_2 for the cover

The peak values of $\frac{N_2}{N_o}$ occurred in the range of 25% to 40% cover, for all depths and velocities. For the experimental conditions, a maximum value of $\frac{N_2}{N_o}$ approximately equal to 3.2 was attained; with an average value of N_o equal to 0.023, this indicated a maximum value of N_2 approximately equal to 0.074. This value compares with that for fragmented ice covers (unconsolidated ice jams) in natural streams.

2. Velocity Distributions

The measured velocity distributions deviated from the normal logarithmic distribution, generally up to 45% below the location of maximum velocity. This agreed with reportage in literature.

Recommendations

1. The assumption of $S_c = S_1 = S_2$ needs further examination.

2. A tentative definition of the wetted perimeter in the case of partial cover has been offered. Improvements in this approach appear feasible, based on the active shear perimeter in skin friction and form drag.

3. In the expression for logarithmic velocity distribution, the physical interpretations of V_*, A and C need careful assessment and clarification for the case of partial covers. These interpretations may be analogous to the effects of large discrete boundary rougnesses for covered channels.

4. The effects of different shapes, orientations and patterns of openings to correspond to conditions in natural streams may be given consideration in future studies.

5. The results of such laboratory studies need to be complemented by observations in natural streams to provide a better framework of overall analysis and prediction.

VI. ACKNOWLEDGEMENTS

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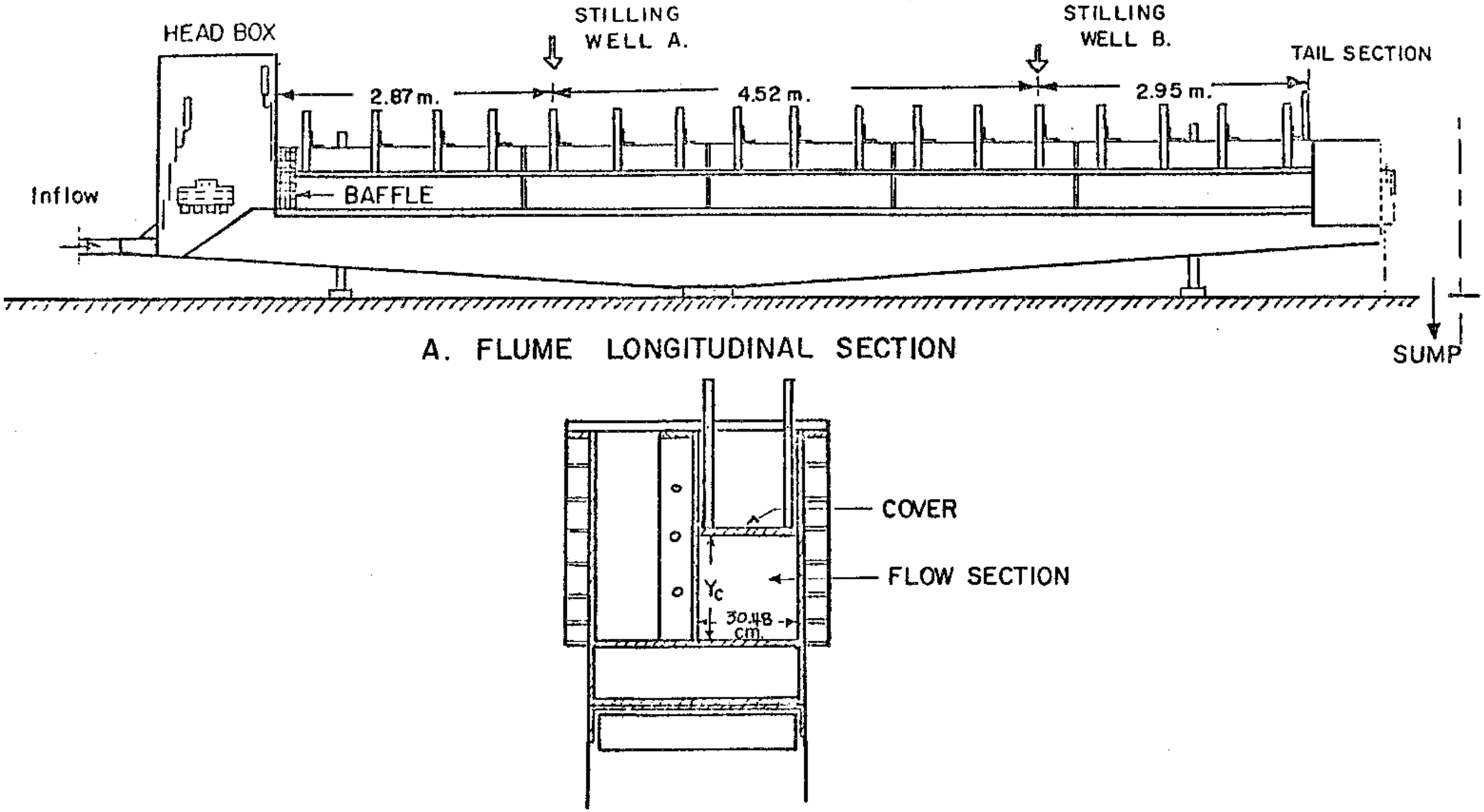
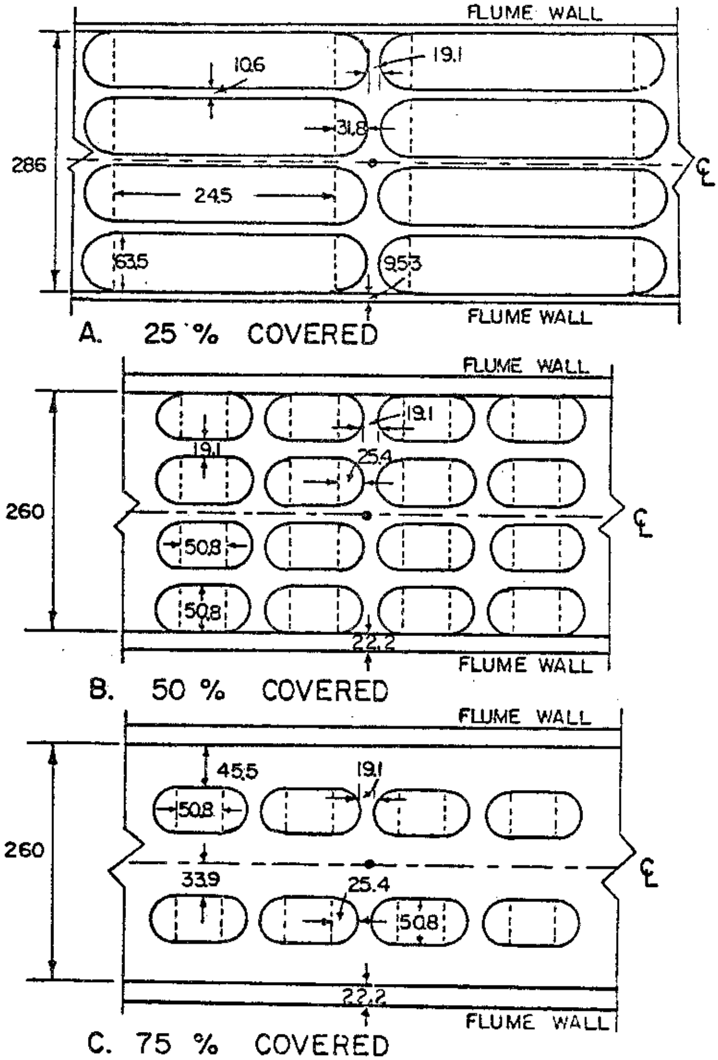


A. FLUME LONGITUDINAL SECTION

B. FLUME CROSS-SECTION

FIG. 1 EXPERIMENTAL FLUME

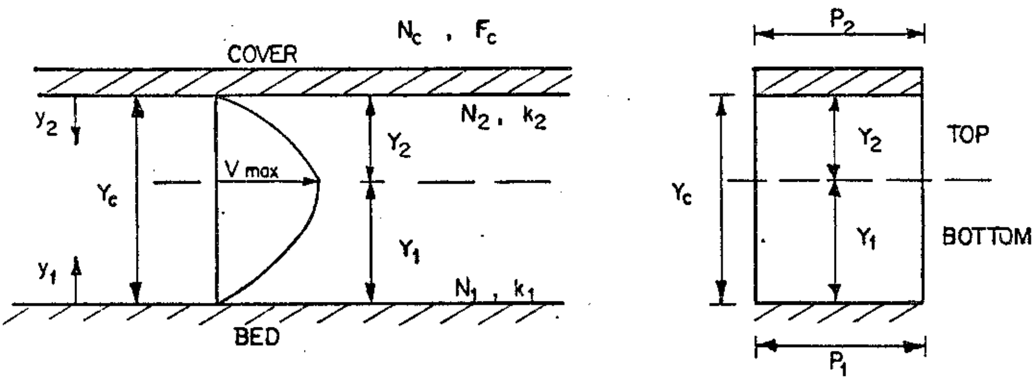


Notes: 1. All dimensions in mm.

2. Ends of all openings semi-circular.

• Typical positions for velocity probe

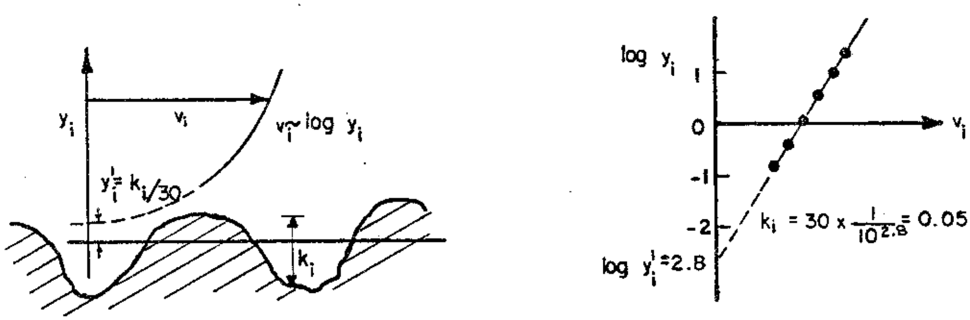
FIG. 2 PLAN VIEW OF TOP COVER—ARRANGEMENT OF OPENINGS



A. LONGITUDINAL SECTION

B. CROSS SECTION OF CHANNEL FOR UNIT WIDTH

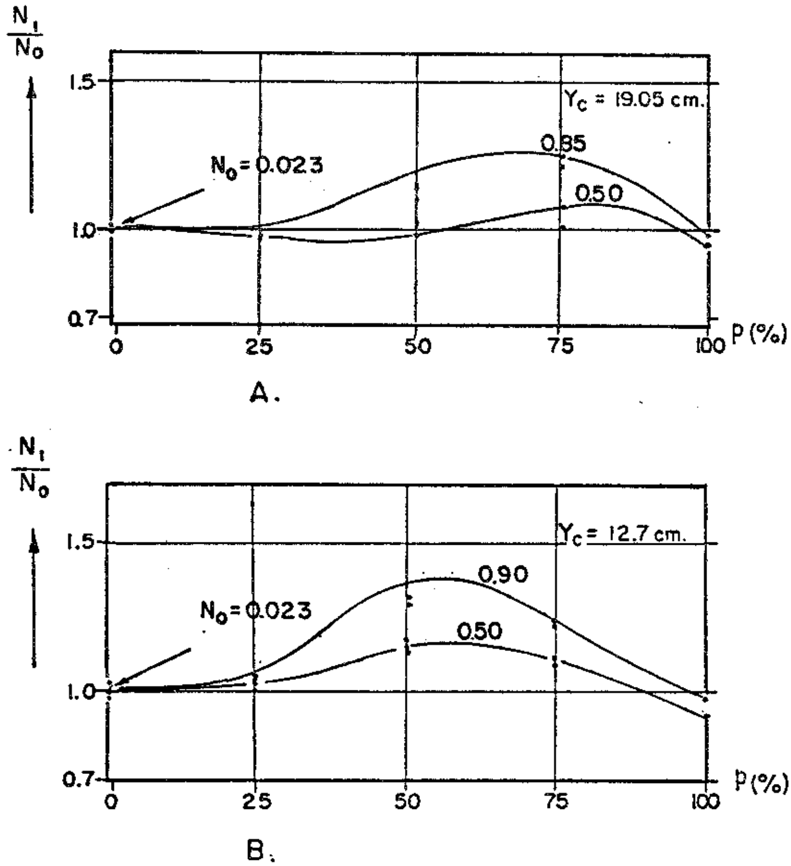
FIG. 3 COMPOSITE CHANNEL REPRESENTATION



$$\frac{v_i}{V_{*i}} = A \ln \frac{y_i}{k_i} + C$$

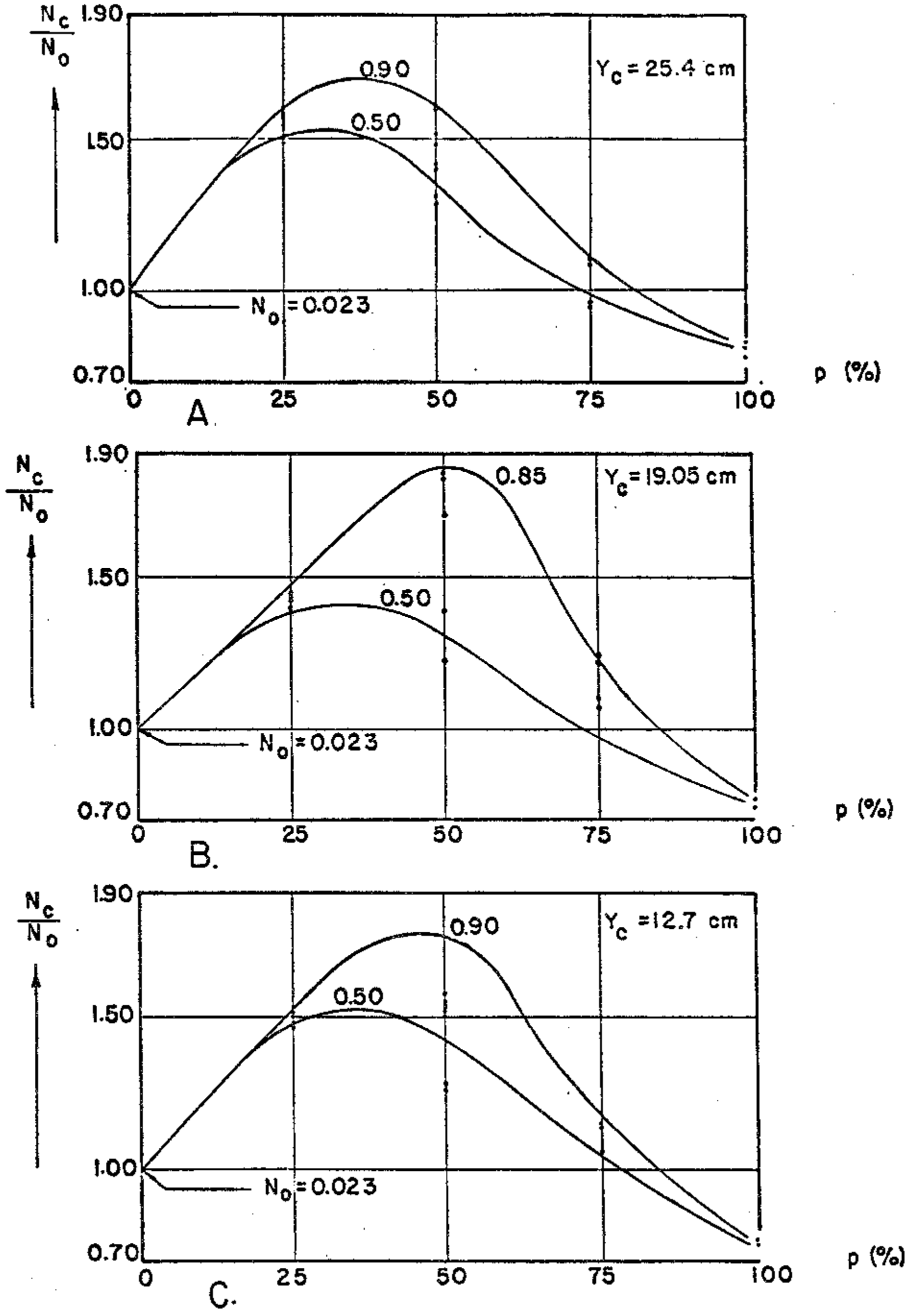
$$k_i = C' \, Y_i e^{-a_i} \qquad a_i = \frac{V\,max}{V\,max - V_i}$$

FIG. 4 ESTIMATION OF APPARENT BOUNDARY ROUGHNESS FROM VELOCITY PROFILE (Pratte, 1979)



Note: The numbers on the curves refer to velocities in m/s.

FIG. 5 COMPARISON OF BED. RESISTANCE COEFFICIENTS FOR OPEN AND COVERED CONDITIONS



Note: The numbers on the curves refer to velocities in m/s

FIG. 6 VARIATION OF COMPOSITE RESISTANCE COEFFICIENTS $\frac{N_c}{N_o}$

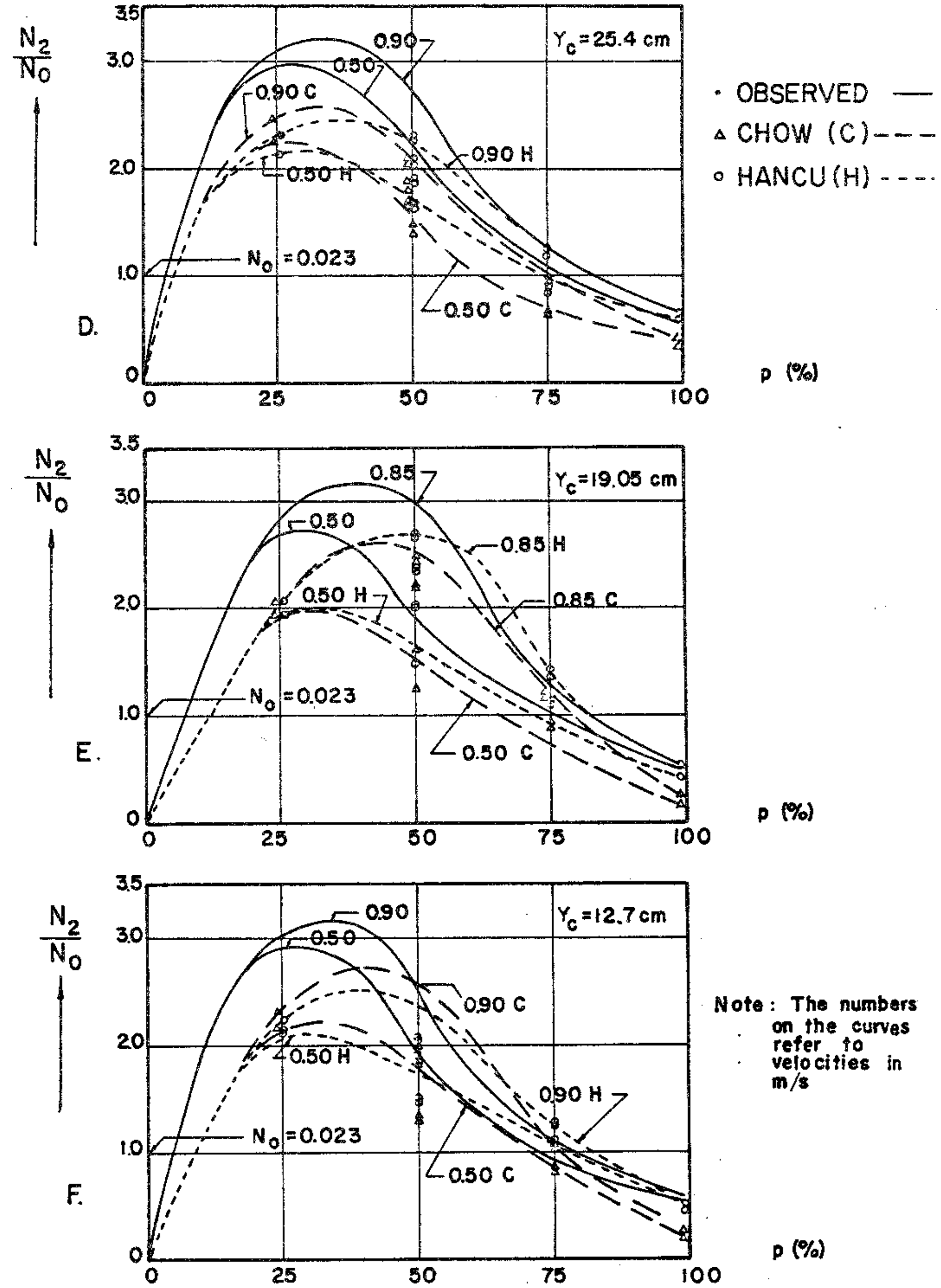


FIG. 7 VARIATION OF COVER RESISTANCE COEFFICIENTS $\frac{N_2}{N_0}$

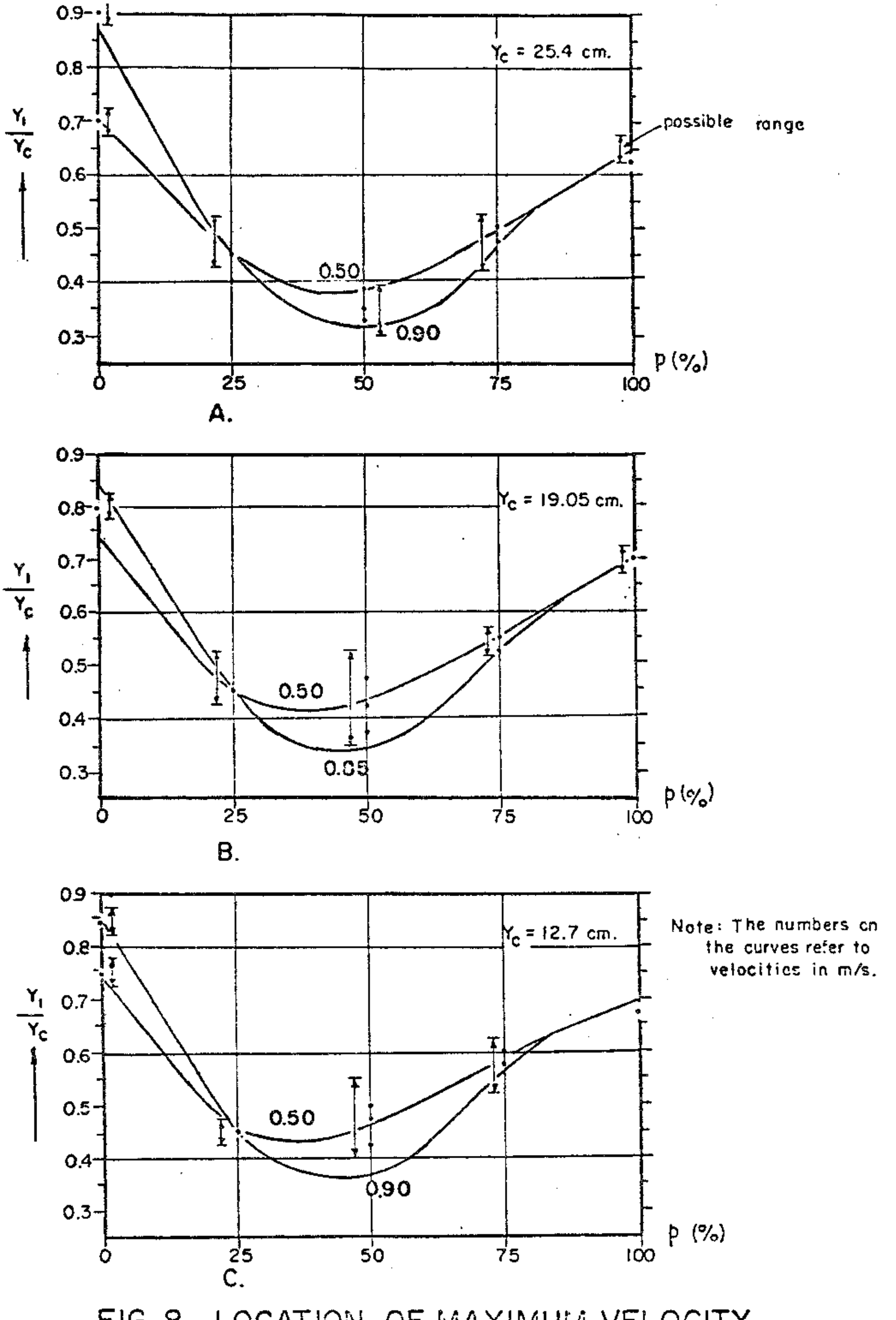


FIG. 8 LOCATION OF MAXIMUM VELOCITY

DISCUSSION

R. Gerard, University of Alberta

1. With a floating ice cover for uniform flow $S_b=S_w=S_e$ as for uniform channel flow, contrary to what was stated in the presentation. Could you please comment.
2. You state that because the effective roughness is larger than the "upper depth" it is not reasonable to use the log formula. However the variations of V with $R^{2/3}$ is also probably not valid in such circumstances so the Manning equation should not be used either. Perhaps in such circumstances it would be sufficient to use the dimensionless Chezy $C_* = \frac{V}{V_*}$ instead. It should also be pointed out that Limerinos (1970) found that the log formula (based on average flow) was valid for very low values of R/k.
3. How do your results relate to those found by Morris (Applied Hydraulics in Engineering) for quite similar situations?

Reply by T.C.C. Tang and K.S. Davar

1. The study reported in this paper was for a fixed cover which led to a "quasi-uniform flow" as indicated in paragraph 1 on page 2; even in a field situation if the cover is fixed, uniform flow may not always prevail. With a floating ice cover, it is likely that uniform flow could exist for normal flow conditions. When a flood situation develops with rapid changes in flow, uniform flow would not exist.
2. Since Manning's equation is basically of empirical derivation, and V varies with N, R and S, the statement in the question that V varies with $R^{2/3}$ is not clear. The authors are not aware of specific restrictions in the use of Manning's equation for limiting large values of k/R. For partial cover with openings in the cover, the definition of an effective height of boundary roughness k becomes quite indeterminate; hence, any method for evaluating resistance based on k becomes inapplicable.
3. The authors consider the experimental boundary conditions for partial covers with openings of the geometrical patterns used to be quite different from those examined by Morris. This is due to the freedom for vertical surging of the fluid within the openings, and also the geometrical arrangement of the openings at the boundary in contrast to the slots in the fixed boundary used in the experiments of Morris.

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1. Would a floating ice cover have allowed you to obtain $S_e=S_w=S_b$?

2. Was there significant surging of water in the holes?

Reply by T.C.C. Tang and K.S. Davar

1. It is possible that a floating ice cover could permit uniform flow conditions with $S_e=S_w=S_b$, for normal flow conditions; uniform flow may not exist during floods.
2. There was significant surging of water within the openings, particularly near the entry and exist zones in the flume. This is particularly true for the experimental conditions for a fixed cover, and would be less significant for the case of a floating cover.