OPEN CHANNEL TRANSITIONS WITH

SUB-CRITICAL FLOW

by

Ottoniel Herrera Arguello

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I. INTRODUCTION

Open channels have been a useful way of carrying water for many centuries. The hydraulic design of the open channel has been studied extensively, and many hydraulic formulas have been developed. At times, there are certain factors which necessitate a change in the size of the open channel being used; therefore, a transition is needed.

Transitions in open channels with sub-critical flow have not been studied since Hinds discussed their design (1, 2). His recommendations are useful but incomplete. According to the general suggestion, one assumes a double parabola as the water surface profile, a continuous warped surface on the sides, a length of transition such that a straight line joining the flow line at the two ends of the transition will make an angle of about 12-1/2° with the axis of the structure, and through hydraulic formulas, finds the corresponding bottom profile. In addition, Hinds states that it is not possible to secure regularity in both the plan and the bottom profile so that the assumed water surface profile may be altered and that a slight change in the elevation of the water surface, at a given point, usually makes an appreciable change in the dimensions of the structure.

The method is purely empirical. The purpose of this thesis is to solve many cases of transitions in open channels on sub-critical flow using the suggestion made by Hinds. The IBM 7040 computer was used for the calculations. An attempt was made to find the irregularities of the plan and bottom profile, if such irregularities existed, the range in which the irregularities existed, the development of graphs in order to help design transitions in open channels with sub-critical flow, and the behavior of certain designed transitions with different discharges.

II. THEORETICAL CONSIDERATIONS AND METHOD OF OPERATION

The energy equation was made to find the form and friction losses,

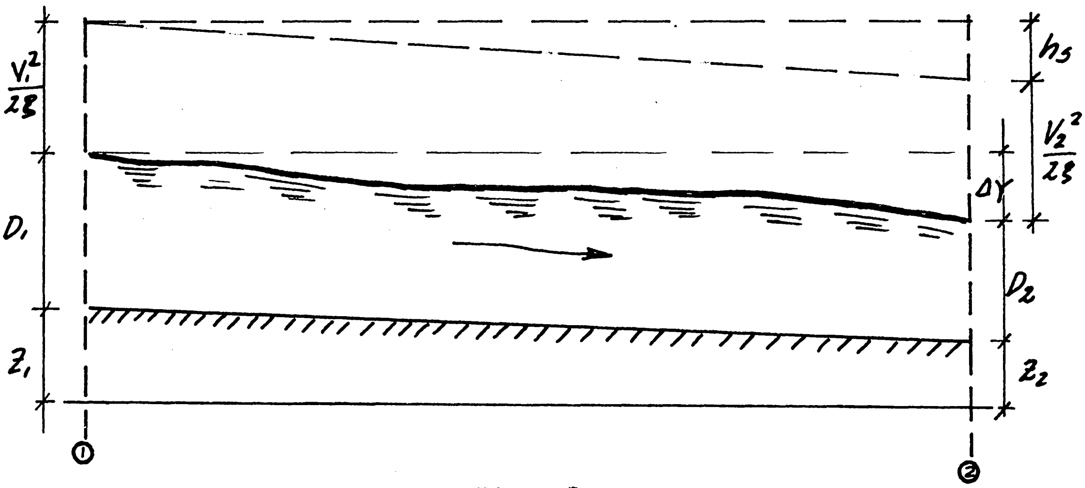

Fig. 1

Referring to Figure 1,

$$Z_1 + D_1 + \frac{V_1^2}{2g} = Z_2 + D_2 + \frac{V_2^2}{2g} + h_s$$

The difference in elevation between the two points may be expressed as:

$$\Delta Y = Z_1 + D_1 - (Z_2 + D_2)$$

$$\Delta Y = \frac{V_2^2}{2g} - \frac{V_1^2}{2g} + h_s$$

$$\Delta Y = \Delta h + h_s$$

$$\Delta Y = \Delta h(1 + C)$$

C is the coefficient of inlet loss, which will be assumed to be equal to 0.1.

The procedure followed can be summarized as:

(1) The assumption is made of a continuous, warped surface on the sides for the transition.

(2) The length of the transition is taken such that a straight line joining the flow line at the two ends of the transition will make an angle of about 12-1/2° with the axis of the structure.

(3) A double parabola is assumed as the water surface profile.

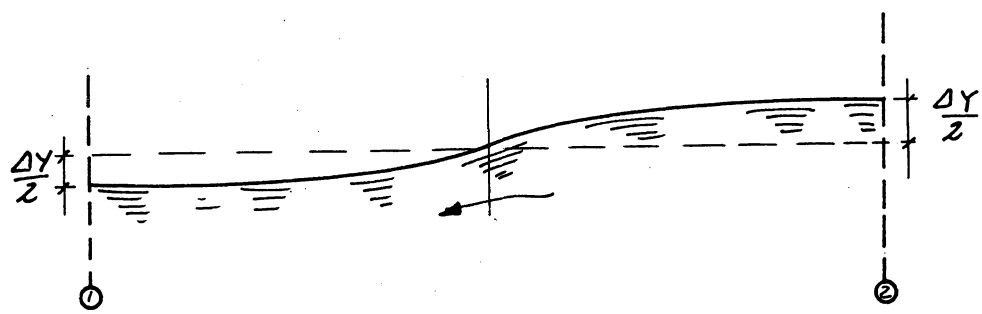

Fig. 2.

(4) The length of the transition is divided into ten sections.

(5) The velocities are calculated at each section along the transition, taking into account the form loss.

(6) The area required for each section is determined by using the equation A = Q/V.

(7) With the assumed warped surface on the sides for the transition the corresponding bottom profile is found, corrected by the friction loss. The warped surface on the sides of the transition is accepted as good when the bottom profile found is smooth; if not, the warped surface is changed until this is achieved. The bottom profile is obtained by the calculation indicated in Table I.

TABLE I

Location of the sections (1)	Δy (2)	$\frac{\Delta y}{1.1}$ (3)	h_V (4)	$V = \sqrt{h_V \times 64.4}$ (5)	$A = Q/V$ (6)	1/2 T (7)

1/2 B (8)	1/2(T + B) (9)	D (10)	$[1/2(T - B)]^2$ (11)	D^2 (12)	$\sqrt{D^2 + [1/2(T - B)]^2}$ (13)

$P = B + 2\sqrt{D^2 + [1/2(T - B)]^2}$ (14)	$P^{4/3}$ (15)	$A^{\frac{10}{3}} \times 10^4$ (16)	$S\times 10^{-4} = \frac{1.77\ P^{4/3}}{A^{\frac{10}{3}} \times 10^4}$ (17)

$S\times 10^{-4}(\text{aver.}) = \frac{S_n + S_{n+1}}{2} \times 10^{-4}$ (18)	$\Delta h_f = \Delta L \times S\times 10^{-4}(\text{aver.})$ (19)

Elevation water surface (20)	Elevation bottom profile (21)

III. PRESENTATION OF DATA

The calculations were made with inlet transitions from trapezoidal to rectangular cross-sections having the same bottom width. The transitions were calculated with water depths of 5, 6, 8, and 10 feet, and each one with 5, 7.5, 10, and 12.5 feet of bottom width. The water depth was the same at the beginning and end of each transition. The discharge for each case was varied from 50 cfs until critical flow for that case was reached.

The ratio of half the difference between the top and bottom width at each section, y, and half the difference between the top and bottom width at the entrance section, y_e, was plotted against the discharge for each water depth with different bottom widths. The results were used to construct another curve similar to the former except that values of Q/D were plotted instead of Q values, and adjusted values of y/y_e, y'/y'_e, were plotted instead of the y/y_e values themselves.

The calculations of the behavior of a given transition with different discharges were made with two different transitions of the same bottom width of five feet but with different design discharges, one with 50 cfs and the other with 200 cfs. The ratios of the water depth at each section with different discharges to the water depth at each section for the design discharge were compared with the ratios of the different discharges to the design discharge.

IV. ANALYSIS AND DISCUSSION

In the range where the calculations of the transitions were made, there was no irregularity found between the continuous warped surfaces on the sides and the corresponding bottom profiles. All the bottom profiles found were straight lines. This important factor of no irregularity between the warped surfaces on the sides and the bottom profiles made it unnecessary to change the double parabola as the water surface profile in all cases.

The warped surfaces that were obtained on the sides showed a great similarity for each transition of the same water depth at the entrance section; in other words, transitions with the same area at the entrance section. From this fact it was deduced that the areas of the cross-sections were determining factors of the corresponding warped surface on the sides. The Froude number showed no influence in the shape of the transitions.

Figures 3 through 38, show the discharge plotted against the ratio of half the difference between the top and bottom width at each section, and half the difference between the top and bottom width at the entrance section. These curves show the following characteristics:

(1) In the sections located between the entrance section and the middle section of the transitions, the values of y/y_e decrease when the discharge increases with constant area; in other words, the values of y/y_e decrease when the velocity increases. The slope of the warped surface on the side is greater to adjust for higher velocities at the beginning of the transitions. These differences in the values of y/y_e for different velocities decrease as one moves to the middle section.

(2) In the middle section of the transition, the values of y/y_e are constant for any discharge.

(3) In the sections located between the middle and final sections of the transitions, the values of y/y_e increase when the velocity increases.

After analyzing the last result and remembering that the transitions studied are running from larger to smaller areas, it can be deduced that water flowing at higher velocities is accelerated to a lesser degree than water flowing at lower velocities.

The present curves can be used to design inlet transitions on sub-critical flow, from trapezoidal to rectangular cross-sections having a Manning coefficient of $n = 0.012$, for water depth of 5, 6, 8, and 10 feet and bottom width from 5 to 12.5 feet.

Figures 39 through 47, show the values of Q/D plotted against the adjusted ratio of half the difference between the top and bottom width at each section, and half the difference between the top and bottom width at the entrance section, y'/y'_e.

Higher values of these ratios correspond to lower values of Q/D, along the entire length of each transition.

From the calculations it was learned that for transitions with common water depth at the entrance section, the longitudinal profiles were maintained except for an increase in the steepness of the bottom slope when a greater discharge existed. The water depth was the same for each corresponding section of the transitions. From the characteristics of the double parabola, it can be seen that the water surface profile decreases at a lesser rate in the beginning than the bottom profile; in other words, the water depth increases at the first section of the transitions. After the middle section is reached, another part of the double parabola shows that the water surface profile decreases at a greater rate than the bottom profile. Consequently, the water depth decreases rapidly after the middle section is passed.

When values of Q/D were used, it was found that for a given value of Q/D the same velocity always existed at the final sections of the transitions, although discharges were different. However, the velocities were different at the entrance section. The fact was of primary importance in constructing Figures 39 through 47. The construction of these curves was as follows:

Table II shows different values at each section for transitions with a water depth of five feet and a value of Q/D equal to 30.

Column 1 shows the positions of each section along the transition. x is the distance of each section from the entrance section, and L is the total length of the transition.

Columns 2, 6, 8, and 10 show the values of y/y_e.

The values of columns 3, 7, 9, and 13 are obtained as follows: (1) The values of the top row are always one. (2) The values of the bottom row are the corresponding values of the velocity at the entrance section of that transition. (3) The values of the intermediate rows are the equally divided intervals between the values of the top and bottom rows.

Column 4 is the ratio between columns 3 and 7, $\varepsilon_1/\varepsilon_2$. Columns 10 and 14 are the ratios between columns 3 and 9, $\varepsilon_1/\varepsilon_3$, and columns 3 and 13, $\varepsilon_1/\varepsilon_4$, respectively.

Columns 5, 11, and 15 show the ratio of $y1/y_{e1}\big/y2/y_{e2}$, $y_1/y_{e1}\big/y_3/y_{e3}$, and $y_1/y_{e1}\big/y_4/y_{e4}$, respectively.

After analyzing the results given in columns 4 and 5, 10 and 11, and 14 and 15, and noting that the values of column 4 are similar to the values of column 5, those of column 10 are similar to column 11, and those of column 14 are similar to column 15, it was deduced that the following relations could be determined:

$$\frac{y_1/y_{e_1}}{y_2/y_{e_2}} \approx \frac{\varepsilon_1}{\varepsilon_2}$$

$$\frac{y_1/y_{e_1}}{y_3/y_{e_3}} \approx \frac{\varepsilon_1}{\varepsilon_3}$$

$$\frac{y_1/y_{e_1}}{y_4/y_{e_4}} \approx \frac{\varepsilon_1}{\varepsilon_4}$$

$$\frac{y_1/y_{e_1}}{\varepsilon_1} \simeq \frac{y_2/y_{e_2}}{\varepsilon_2} \simeq \frac{y_3/y_{e_3}}{\varepsilon_3} \simeq \frac{y_4/y_{e_4}}{\varepsilon_4} \simeq y'/y_e'$$

Columns 16, 17, 18, and 19 show the values of $y_1/y_{e_1}/\varepsilon_1$, $y_2/y_{e_2}/\varepsilon_2$, $y_3/y_{e_3}/\varepsilon_3$, and $y_4/y_{e_4}/\varepsilon_4$, respectively.

Column 20 shows the values of y'/y'_e that were plotted on the graph.

The advantage of this procedure is that the values of y'/y'_e can be used to design transitions of five feet bottom width and a value of Q/D equal to 30, no matter what discharge or water depth is used.

From the former procedure it can also be deduced that the values of columns 3, 7, 9, and 13 can be obtained as follows:

$$\varepsilon = 1 + \frac{x}{L}(V - 1)$$

V = velocity at the entrance section

$$\varepsilon = \left(1 - \frac{x}{L}\right) + \frac{xV}{L}$$

Similar procedures were followed for different values of Q/D and water depths.

TABLE II

Bottom width = 5 ft.
Q/D = 30

	D = 5 ft.				D = 6 ft.		D = 8 ft.		
(1) x/L	(2) y_1/y_{e_1}	(3) ε_1	(4)	(5)	(6) y_2/y_{e_2}	(7) ε_2	(8) y_3/y_{e_3}	(9) ε_3	(10)
0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.1	0.93	1.20	1.02	1.01	0.92	1.17	0.90	1.14	1.05
0.2	0.77	1.40	1.04	1.02	0.76	1.34	0.71	1.28	1.09
0.3	0.59	1.60	1.05	1.03	0.57	1.52	0.50	1.42	1.13
0.4	0.42	1.80	1.06	1.07	0.39	1.69	0.33	1.56	1.15
0.5	0.26	2.00	1.08	1.08	1.24	1.86	0.20	1.70	1.18
0.6	0.15	2.20	1.08	1.07	0.14	2.03	0.114	1.84	1.20
0.7	0.085	2.40	1.09	1.15	0.074	2.20	0.064	1.98	1.21
0.8	0.037	2.60	1.09	1.12	0.024	2.38	0.03	2.12	1.23
0.9	0.001	2.80	1.10	1.00	0.01	2.55	0.008	2.26	1.24
1.0	0.00	3.00	1.10		0.00	2.72	0.00	2.40	1.25

	D = 10 ft.								
(11)	(12) y_4/y_{e_4}	(13) ε_4	(14)	(15)	(16) $y_1/y_{e_1}/\varepsilon_1$	(17) $y_2/y_{e_2}/\varepsilon_2$	(18) $y_3/y_{e_3}/\varepsilon_3$	(19) $y_4/y_{e_4}/\varepsilon_4$	(20) y'/y'_e
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.03	0.89	1.10	1.09	1.05	0.78	0.82	0.79	0.81	0.80
1.09	0.66	1.20	1.17	1.17	0.55	0.56	0.55	0.55	0.55
1.18	0.45	1.30	1.23	1.31	0.37	0.37	0.35	0.35	0.36
1.27	0.29	1.40	1.29	1.44	0.23	0.225	0.21	0.21	0.22
1.30	0.174	1.50	1.33	1.50	0.13	0.130	0.12	0.11	0.12
1.31	0.094	1.60	1.37	1.60	0.07	0.07	0.06	0.06	0.065
1.33	0.054	1.70	1.41	1.57	0.04	0.03	0.03	0.03	0.03
1.23	0.024	1.80	1.44	1.54	0.02	0.01	0.014	0.01	0.015
1.25	0.006	1.90	1.47	1.66	0.004	0.004	0.004	0.005	0.004
	0.00	2.00			0.00	0.00	0.00	0.00	0.00

It must be noted that because of the procedures that were used to construct these curves, the final results showed an equality in the sign of the slopes throughout the transitions.

These curves can be used to design inlet transitions with sub-critical flow for different values of Q/D. In order to obtain the final values of y/y_e which are going to be used on certain transitions, the values of y'/y'_e have to be modified as follows:

Assign number 1 to the entrance section. The value of the velocity at the entrance section is assigned to the final section. Divide the interval between these two values into ten equal parts and assign the corresponding value to each section in the transition. Then multiply the values of y'/y'_e by the corresponding number assigned at each section. The results should be the y/y_e values.

From the analysis of the results of the behavior of a certain transition with different discharges, the following was found:

(1) For discharges less than the design discharge the ratios between the water depth with different discharges and the water depth with the design discharge,

were larger than the ratio of the corresponding discharges to the design discharge.

(2) For discharges larger than the design discharge the ratios between the water depth with different discharges and the water depth with the design discharge, were less than the ratio of the corresponding discharges to the design discharge.

(3) The ratio between the water depth with a certain discharge and the water depth with the design discharge remained constant along a given transition.

V. CONCLUSIONS AND RECOMMENDATIONS

The range of transitions that was studied was limited. The cases studied were considered common. However, they were restricted by the following conditions:

(1) Inlet transitions from trapezoidal to rectangular sections with the same bottom width.

(2) A common water depth at the beginning and at the end of the transition.

(3) A side slope of 1:1 at the entrance section.

(4) A Manning coefficient of $n = 0.012$.

No information about the effect of the variation of these conditions over the shape of the transitions was obtained through this thesis.

It is presumed that a variation of the values of the Manning coefficient would affect only the scale of the values of y/y_e.

The curves of Figures 3 through 38 can be used for designing open-channel transitions on sub-critical flow within the range studied. The disadvantage is that for each water depth, a different set of curves is needed. However, for different bottom width, ranging from

from 5 to 12.5 feet, interpolation can be used on one set of curves. Therefore, the idea of obtaining a more general set of curves to design this type of transition was the guide in constructing the curves of Figures 39 through 45.

In these curves, by the procedure explained before, the values of y/y_e for each transition with different design discharges were systematically changed and finally just one value of y'/y'_e was obtained for all the transitions.

Therefore, the resulting curves provide values of y'/y'_e which when modified as explained before, give values of y/y_e for transitions of water depths from 5 to 10 feet, and bottom widths from 5 to 12.5 feet, with the same range of discharges.

The analysis of the behavior of a certain transition with different discharges led to the conclusion that any transition can be used with a discharge less than the design discharge. However, this would lead to a loss in efficiency instead of a gain in efficiency which a discharge greater than the design discharge would have provided.

The fact that the ratios between water depths with discharges greater than the design discharge and water depth with the design discharges, will never be greater than the ratios of the corresponding discharges and the design discharge, can be used as a confidence limit in testing transitions with discharges greater than the design discharge.

In future studies it would be convenient to relax the previously mentioned restrictions by considering variations of the mentioned conditions, and by attempting to obtain further relations between the factors which intervene in the functioning of a transition, and also confirm the results obtained in this thesis by models.

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IX. LIST OF SYMBOLS

A = cross-sectional area (ft^2);

B = bottom width (ft);

D = water depth (ft);

g = gravity acceleration (ft/sec^2);

h_f = friction losses (ft);

h_s = form and friction losses (ft);

h_v = velocity head (ft);

Δh_v = difference in velocity head (ft);

L = length of the transition (ft);

P = cross-sectional perimeter (ft);

S = energy slope (ft/ft);

V = velocity (ft/sec);

x = length along the transition from the entrance section (ft);

y = half the difference between the top and bottom width at any section (ft);

y' = adjusted value of y (ft);

y_e = half the difference between the top and bottom width at the entrance section (ft);

y'_e = adjusted value of y_e (ft);

Δy = difference in water surface elevation (ft).

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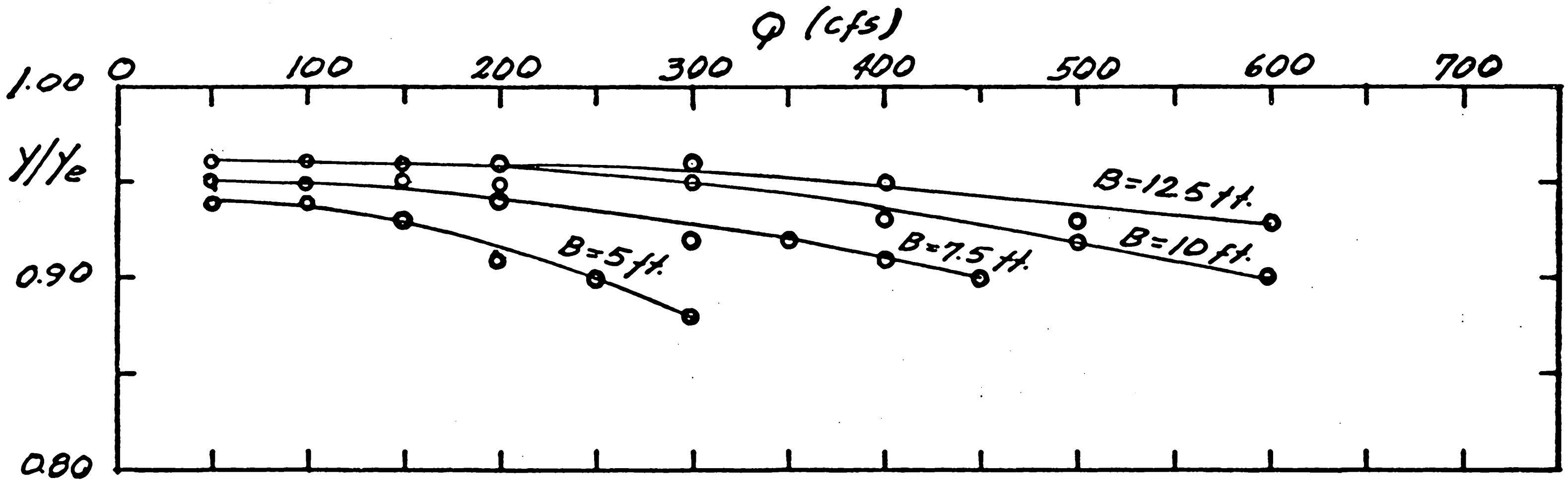

Fig 3. - Q vs Y/Y_e for $x/L = 0.1$ and $D = 5$ ft.

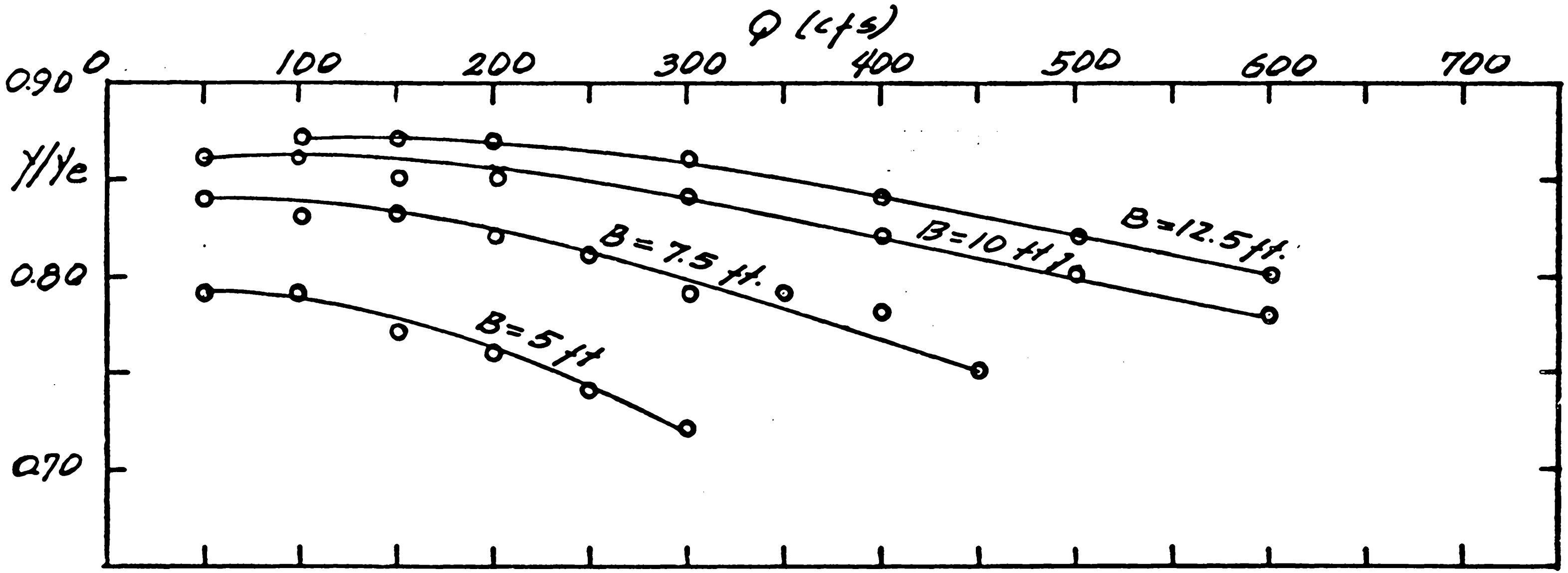

Fig 4.- Q vs Y/Ye for x/L=0.2 and D=5 ft.

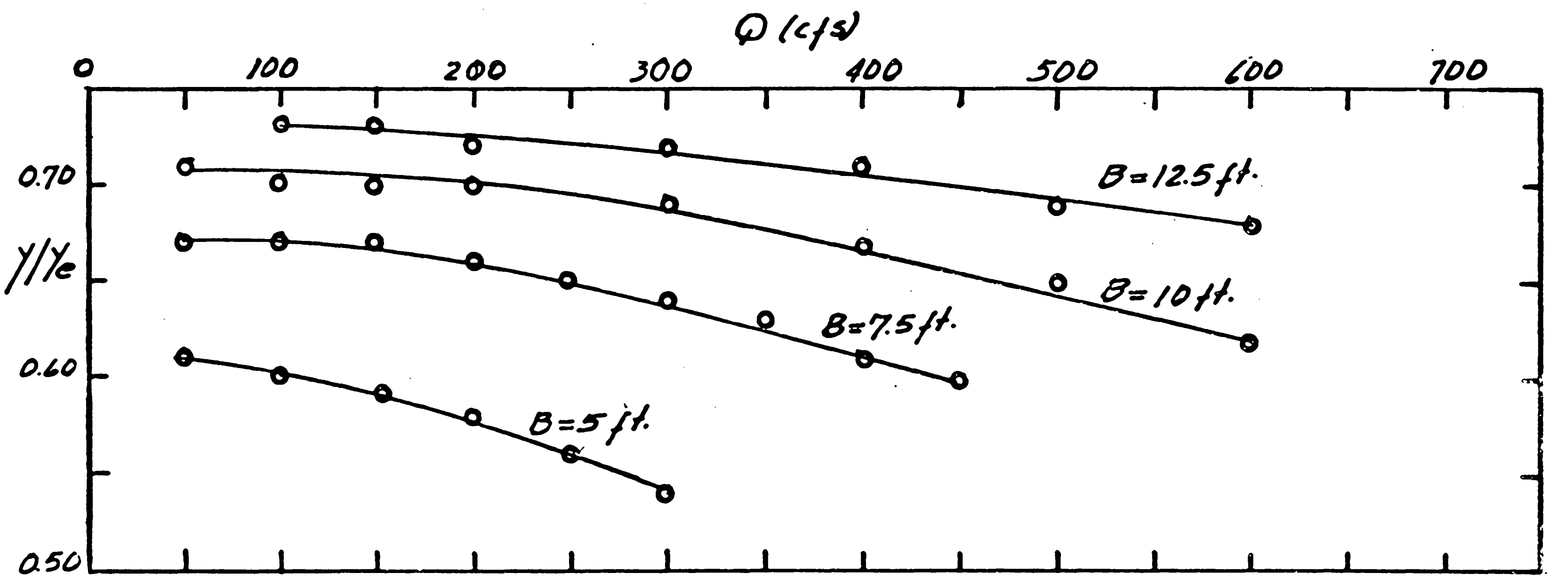

Fig 5. - Q vs Y/Ye for x/L = 0.3 and D = 5 ft.

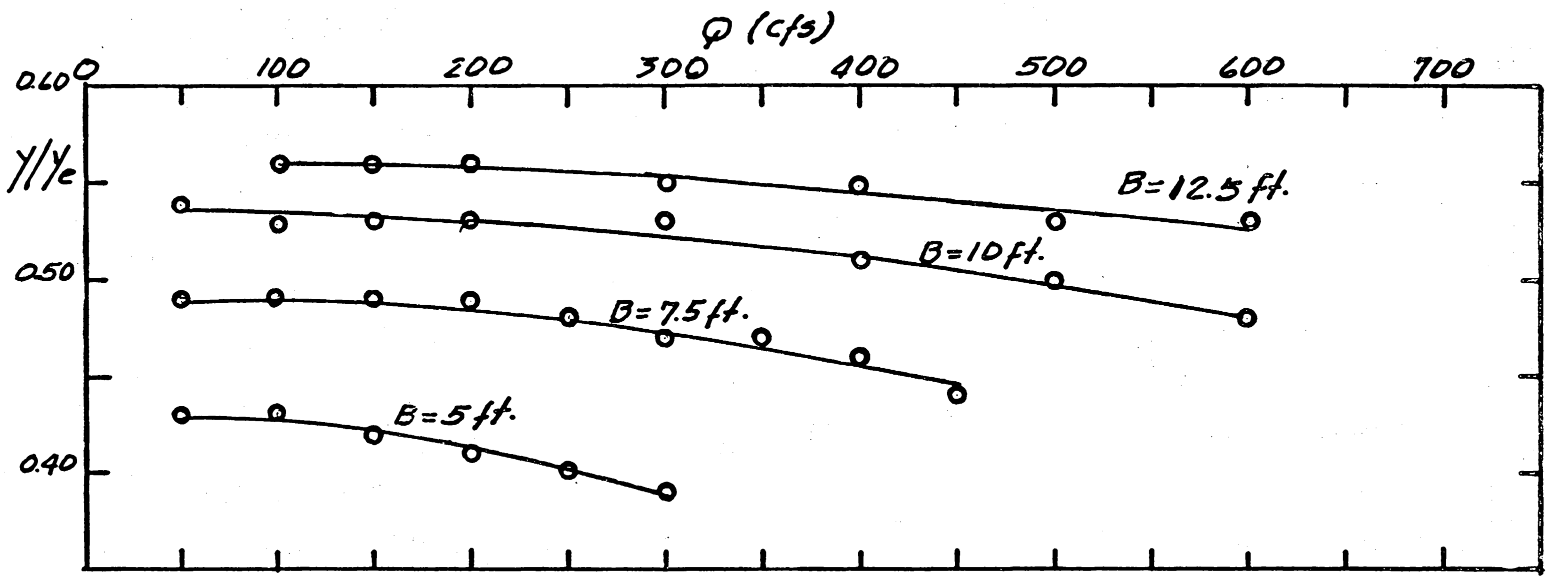

Fig 6.- Q vs y/y_e for $x/L = 0.4$ and $D = 5$ ft.

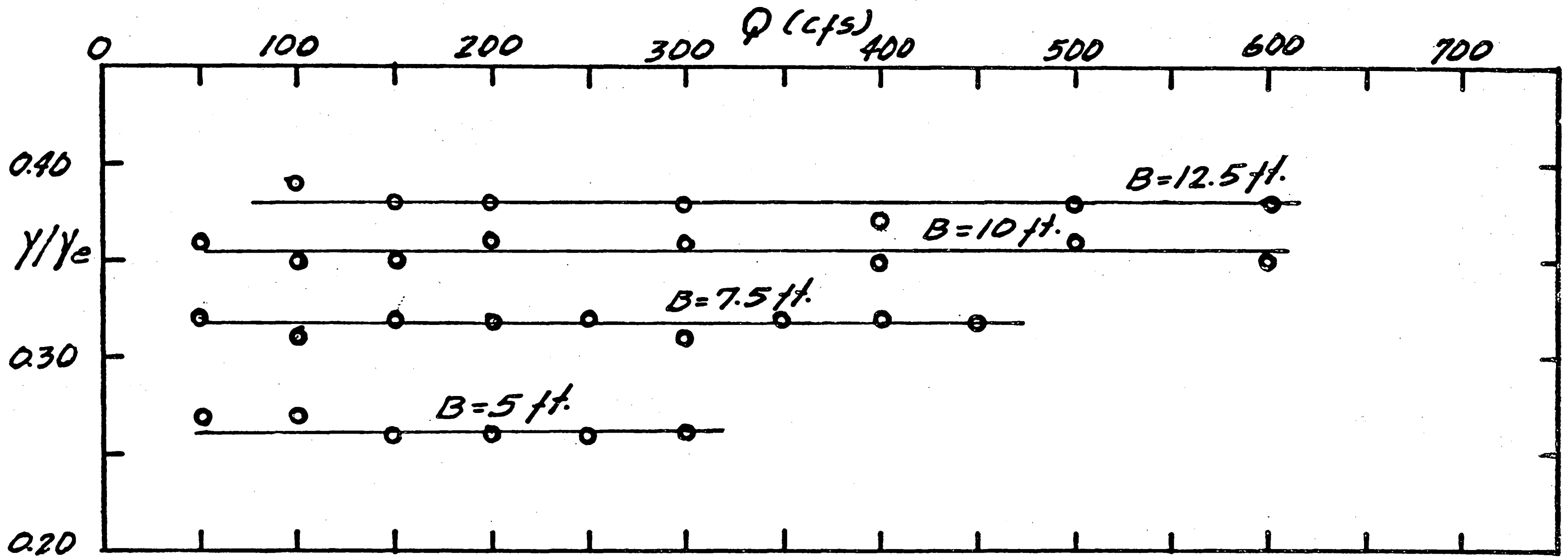

Fig 7.- Q vs Y/Ye for x/L=0.5 and D=5 ft.

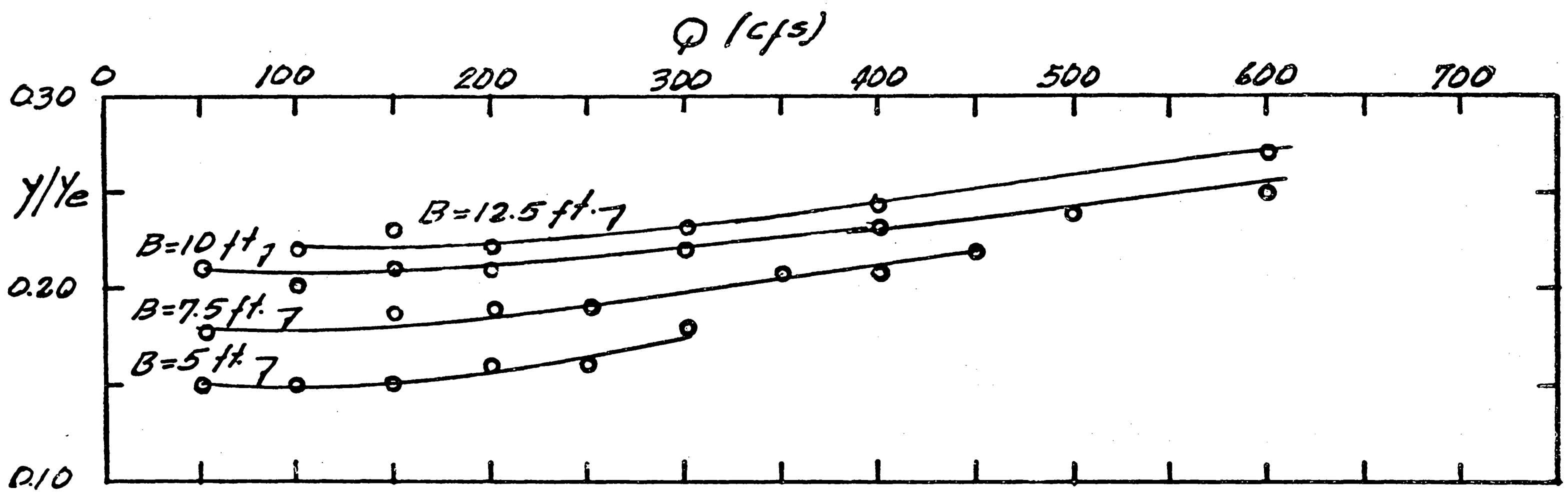

Fig 8.- Q vs Y/Ye for $x/L = 0.6$ and $D = 5$ ft.

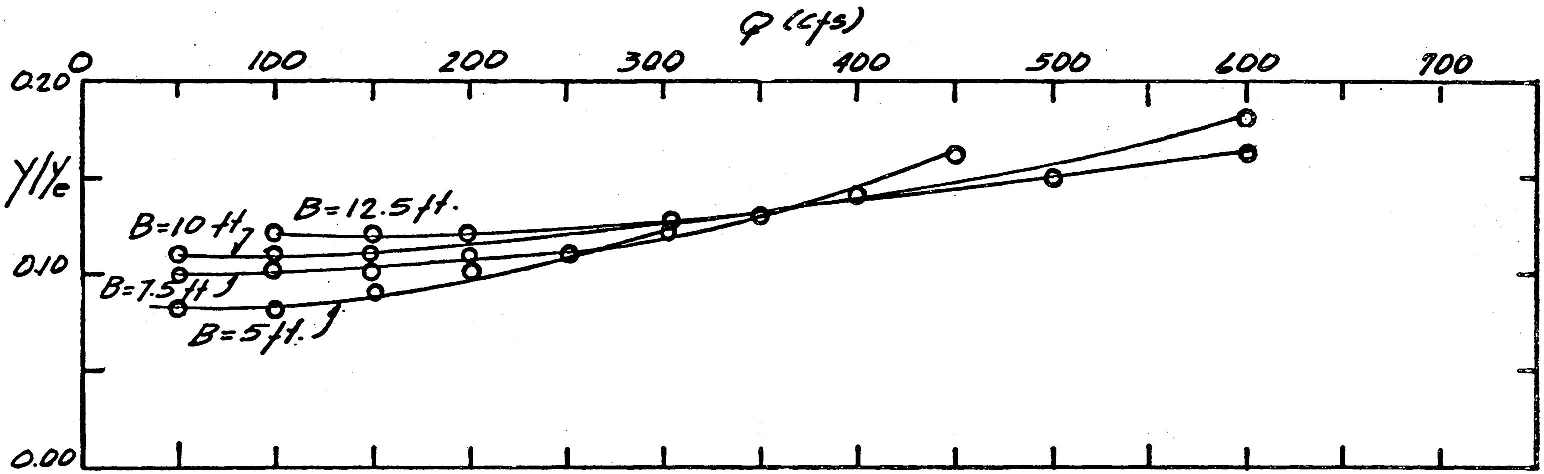

Fig 9.- Q vs Y/Ye for $\chi/L = 0.7$ and D=5 ft.

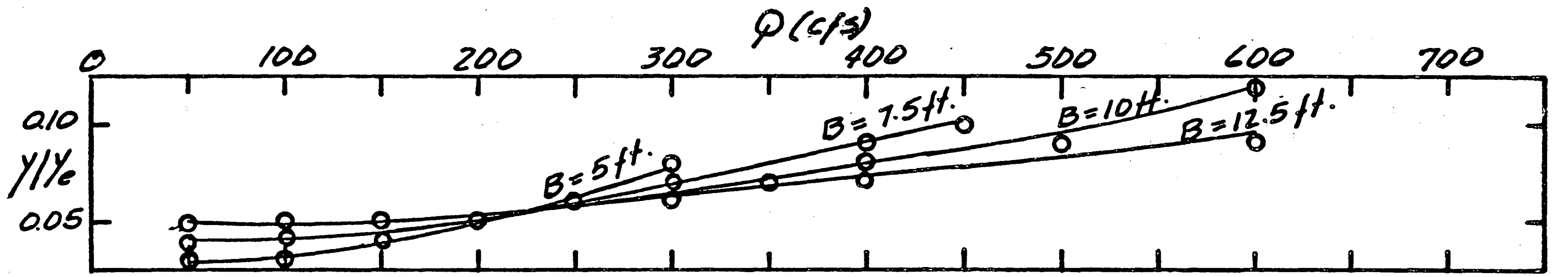

Fig 10.- Q vs Y/Ye for x/L=0.8 and D=5ft.

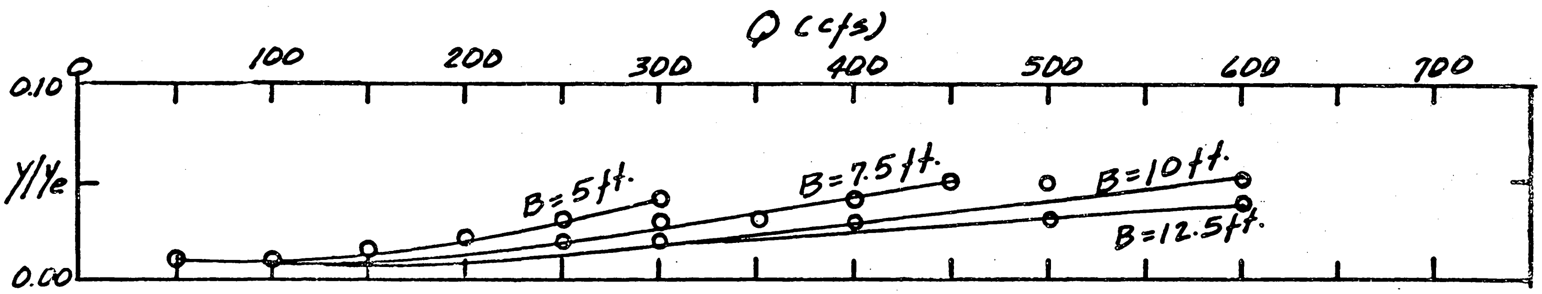

Fig 11.- Q vs Y/Ye for x/L=0.9 and D=5ft.

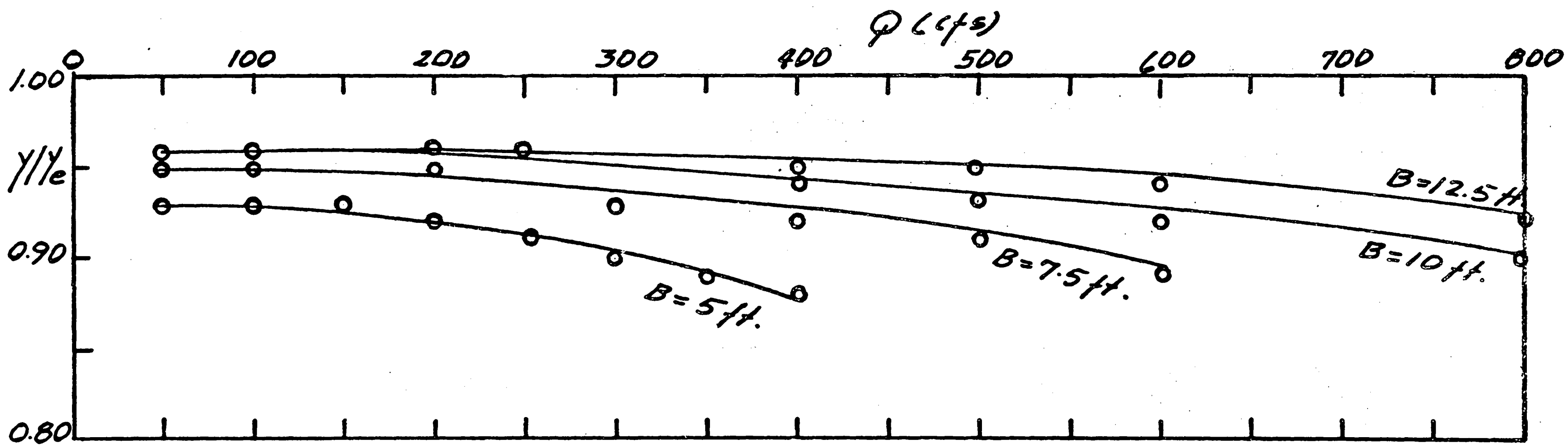

Fig 12.- Q vs y/ye for x/L=0.1 and D=6 ft

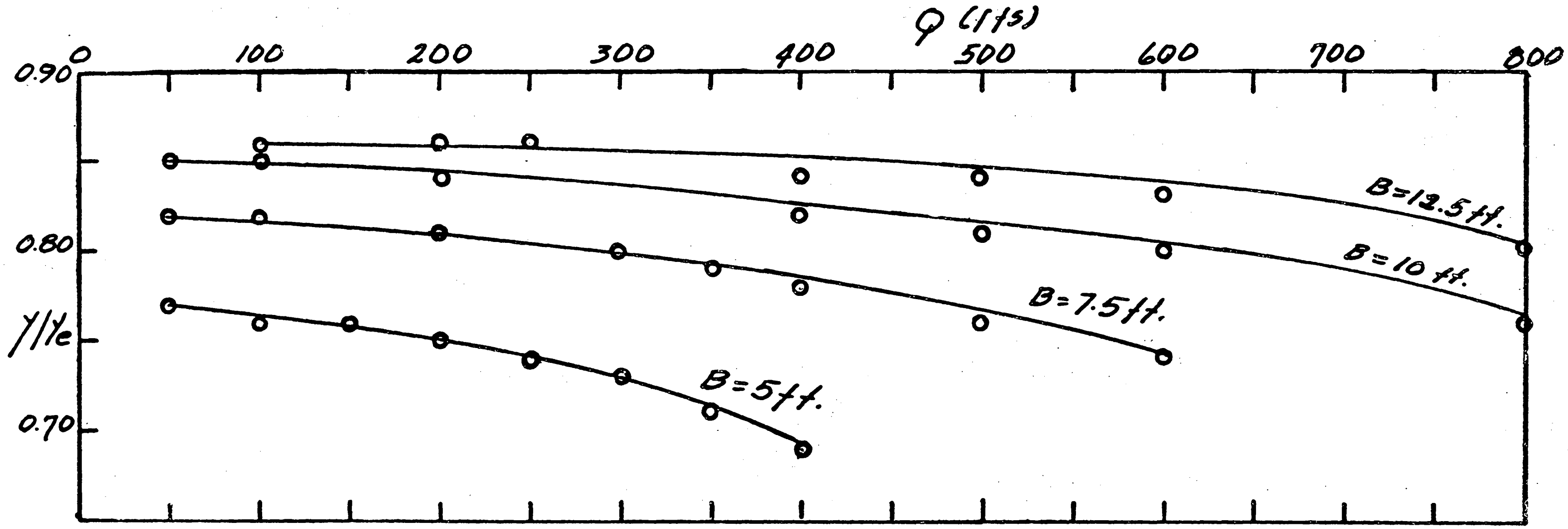

Fig 13. - Q vs Y/Y_e for $x/L = 0.2$ and $D = 6$ ft.

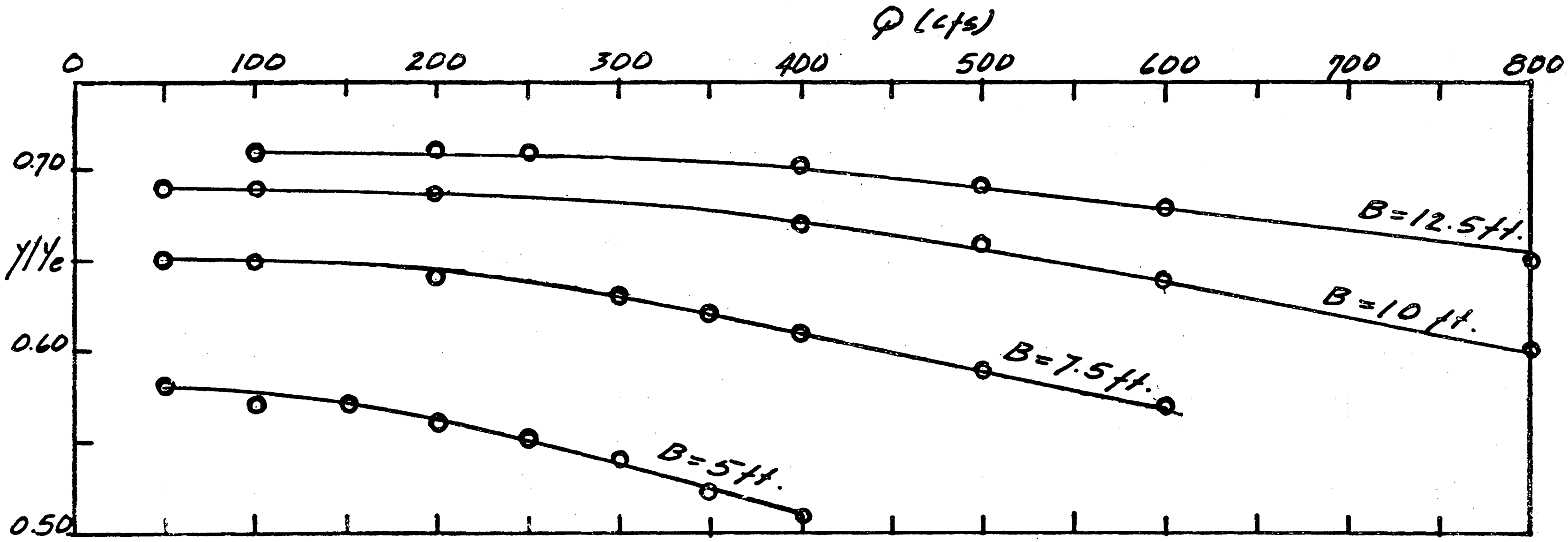

Fig 14. - Q vs Y/Ye for x/L = 0.3 and D = 6 ft.

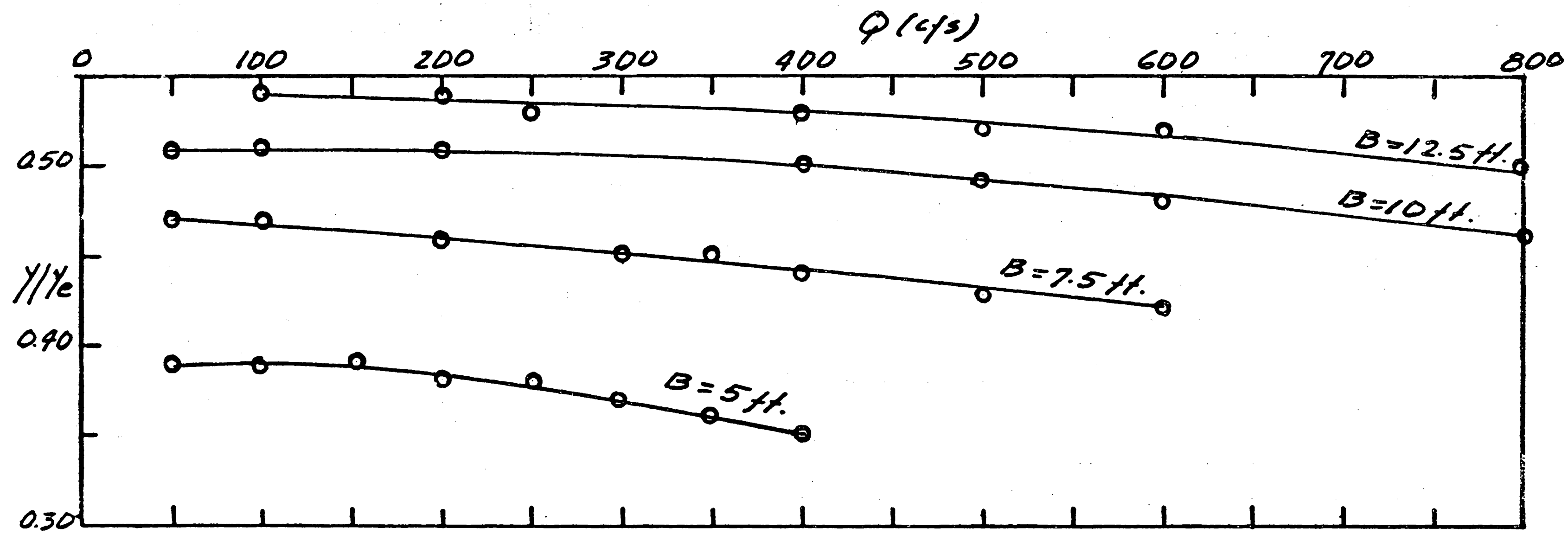

Fig 15.- Q vs Y/Ye for x/L = 0.4 and D = 6 ft.

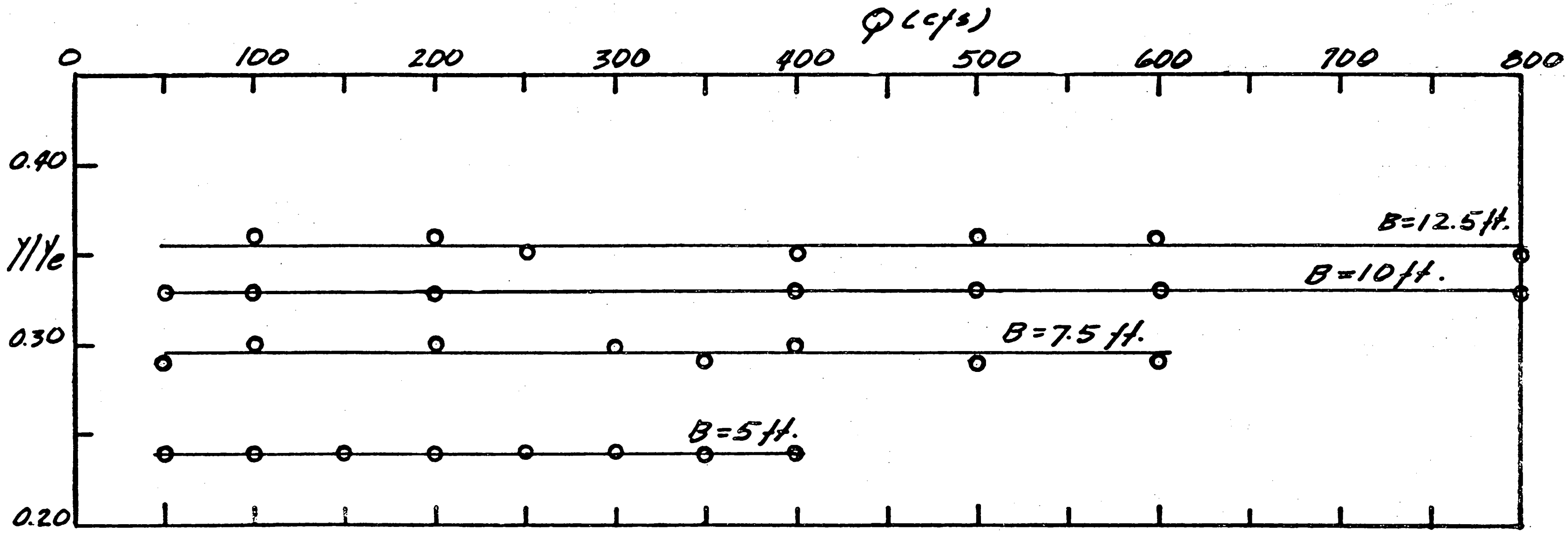

Fig 16.- Q vs Y/Ye for x/L = 0.5 and D = 6 ft.

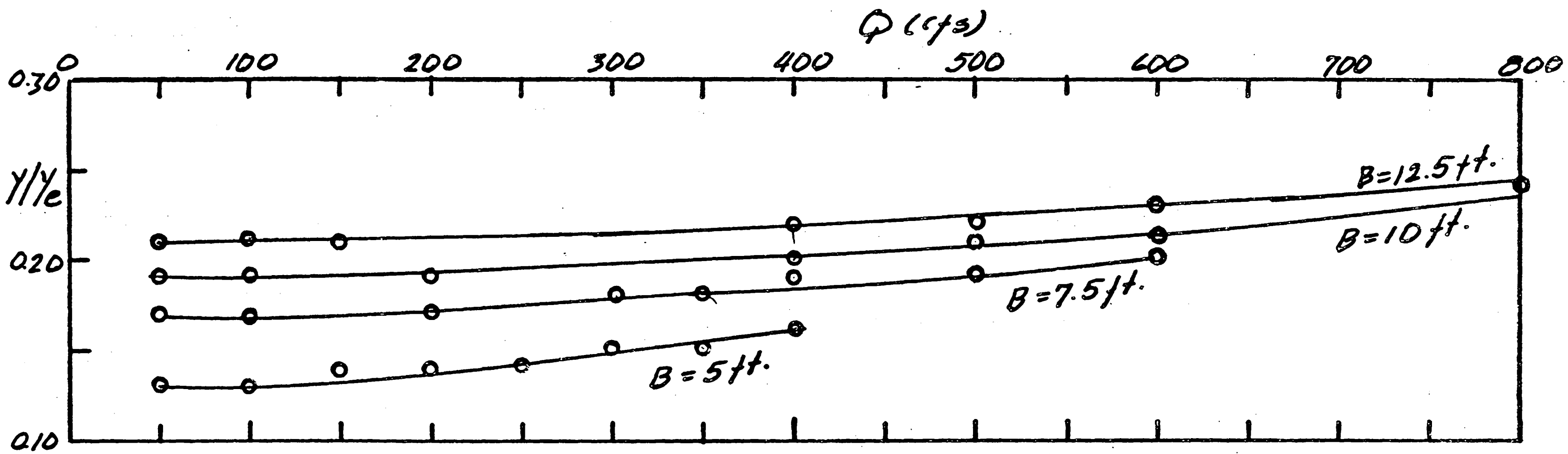

Fig 17.- Q vs Y/Y_e for $x/L = 0.6$ and $D = 6$ ft.

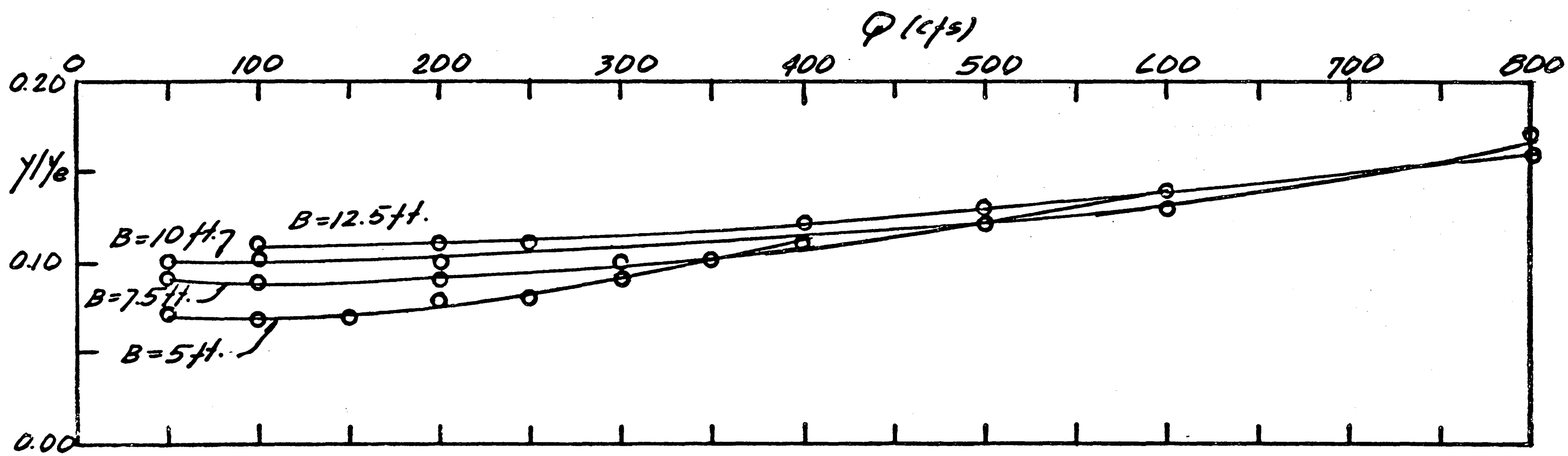

Fig 18.- Q vs y/ye for x/L = 0.7 and D = 6 ft.

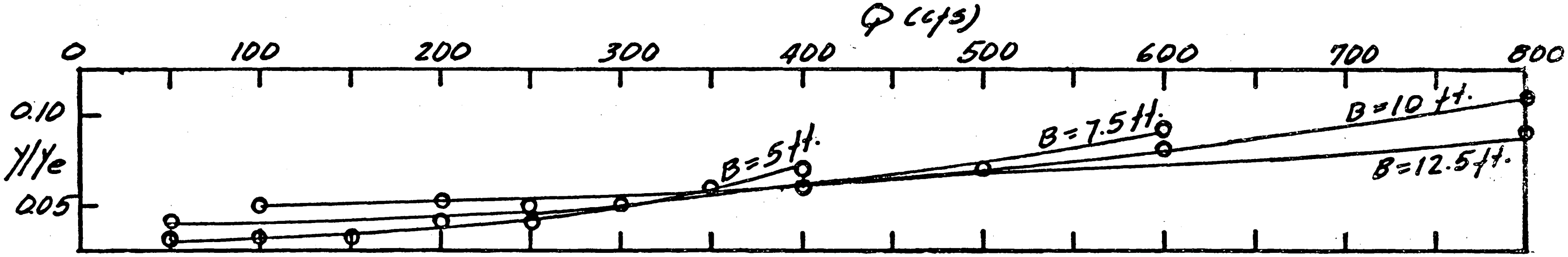

Fig 19.- Q vs Y/Ye for $x/L = 0.8$ and $D = 6$ ft.

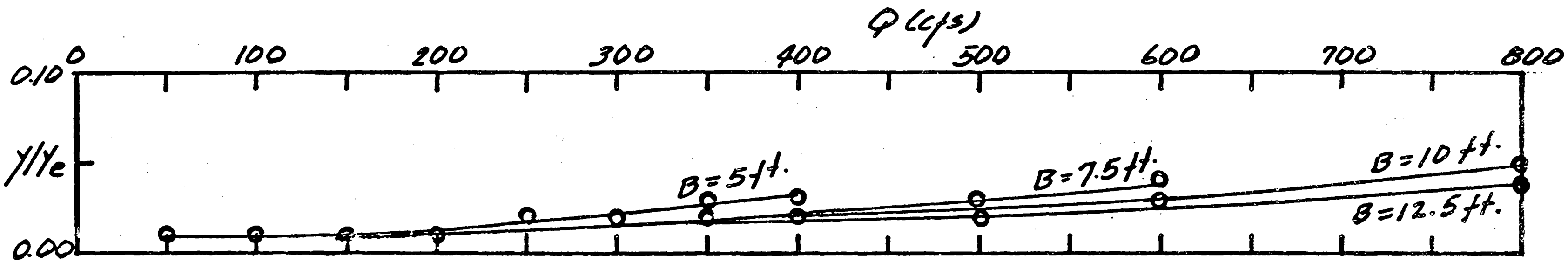

Fig 20.- Q vs Y/Ye for $x/L = 0.9$ and $D = 6$ ft.

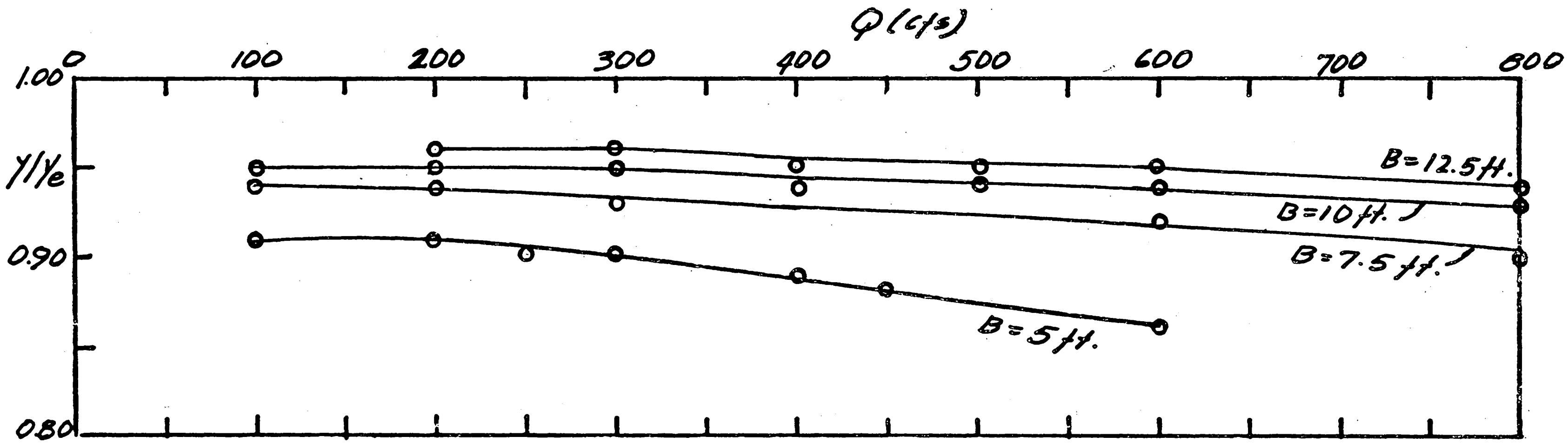

Fig 21. - Q vs Y/Ye for x/L = 0.1 and D = 8 ft.

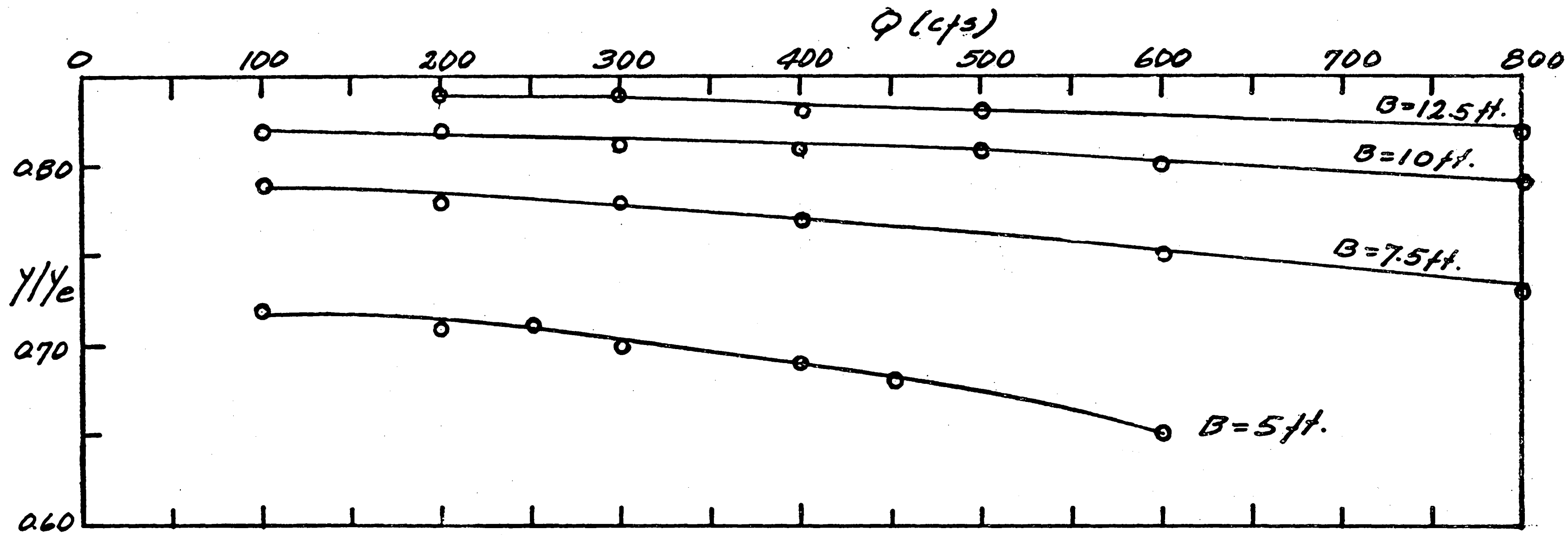

Fig 22. - Q vs Y/Ye for X/L = 0.2 and D = 8 ft.

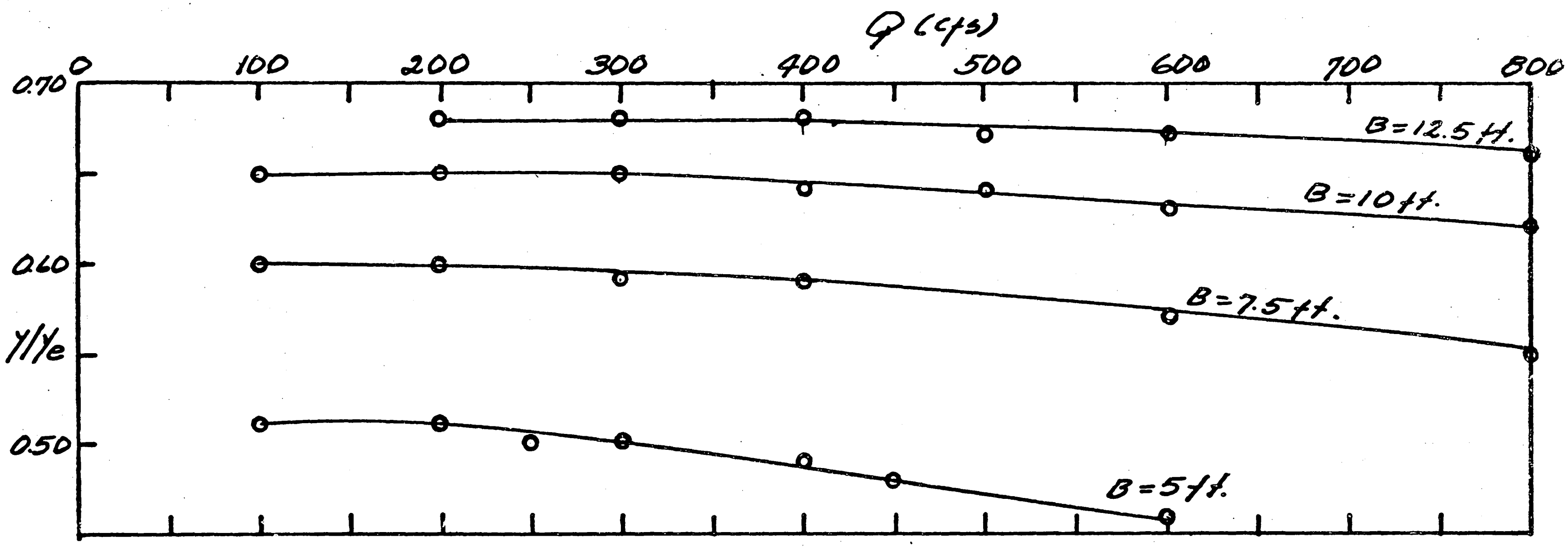

Fig 23. - Q vs Y/Ye for x/L = 0.3 and D = 8 ft.

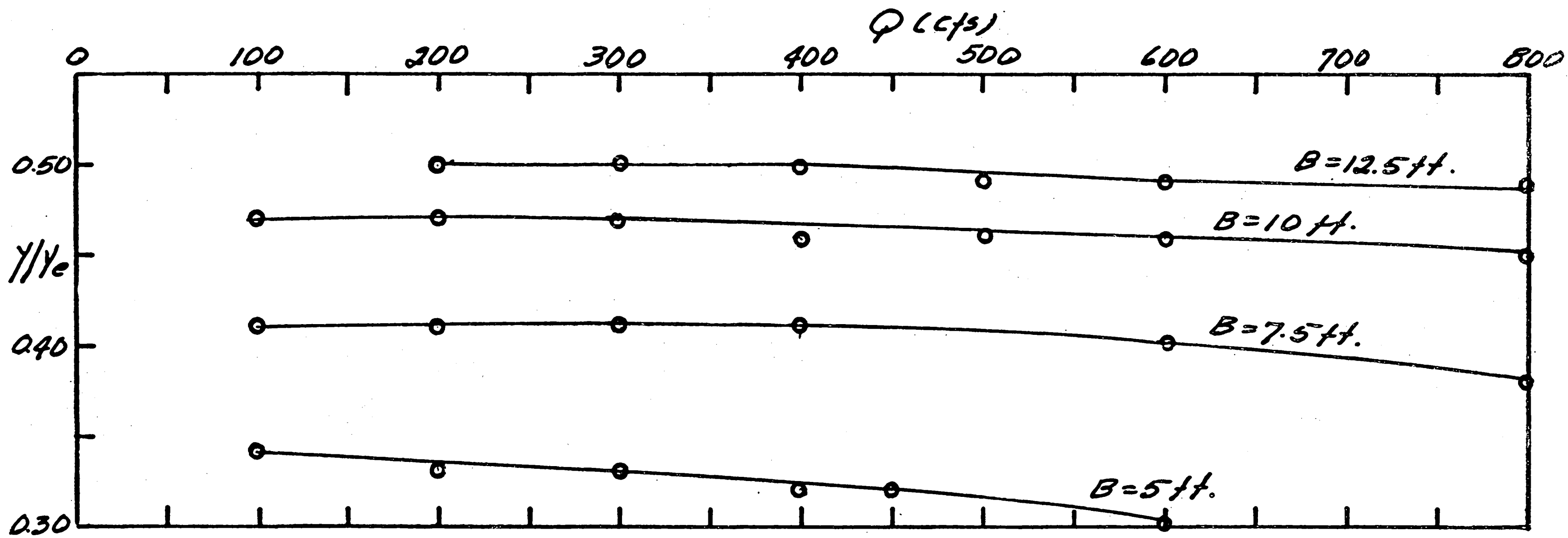

Fig 24.- Q vs Y/Ye for X/L = 0.4 and D= 8 ft.

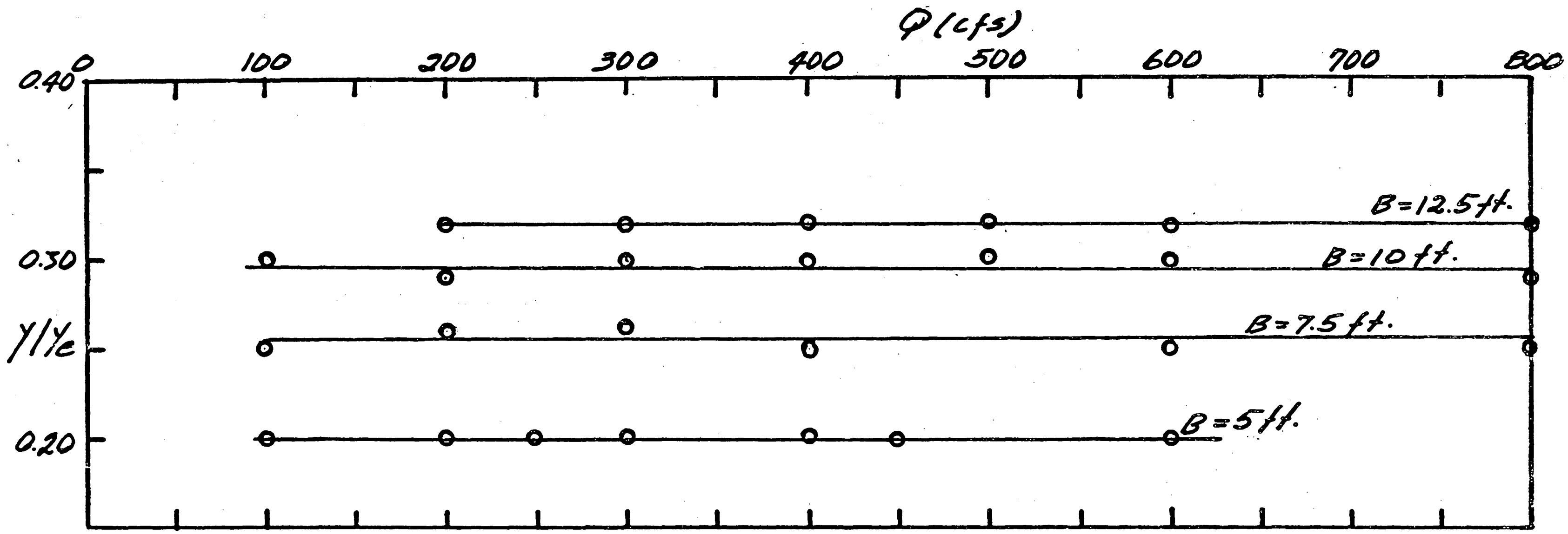

Fig 25.- Q vs Y/Ye for $x/L = 0.5$ and D= 8 ft.

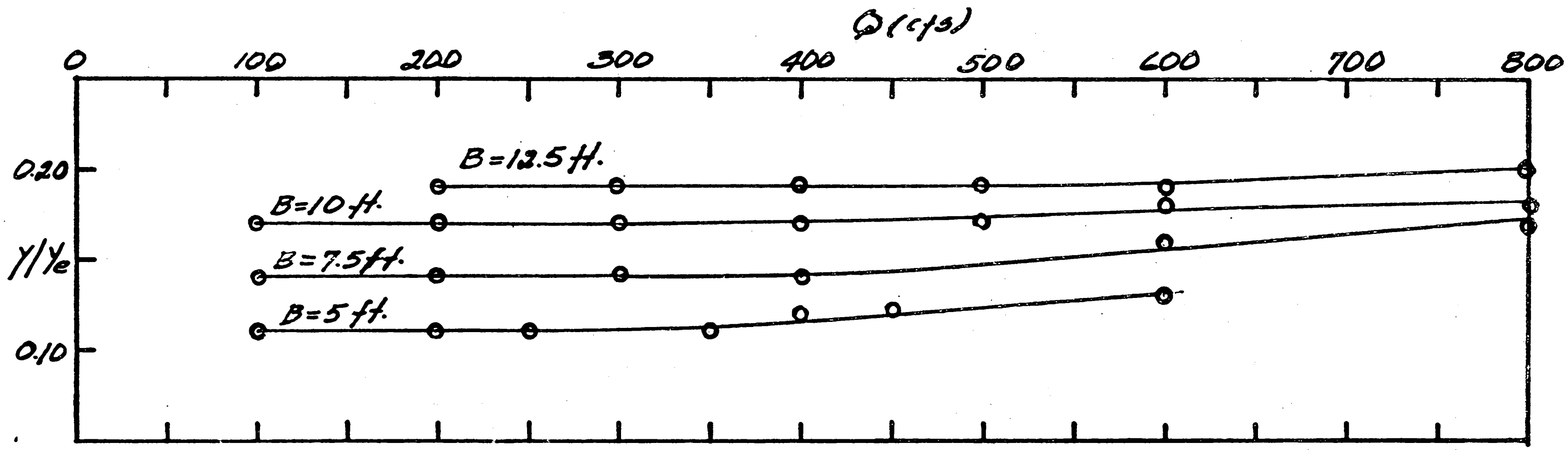

Fig 26. - Q vs Y/Ye for x/L = 0.6 and D = 8 ft.

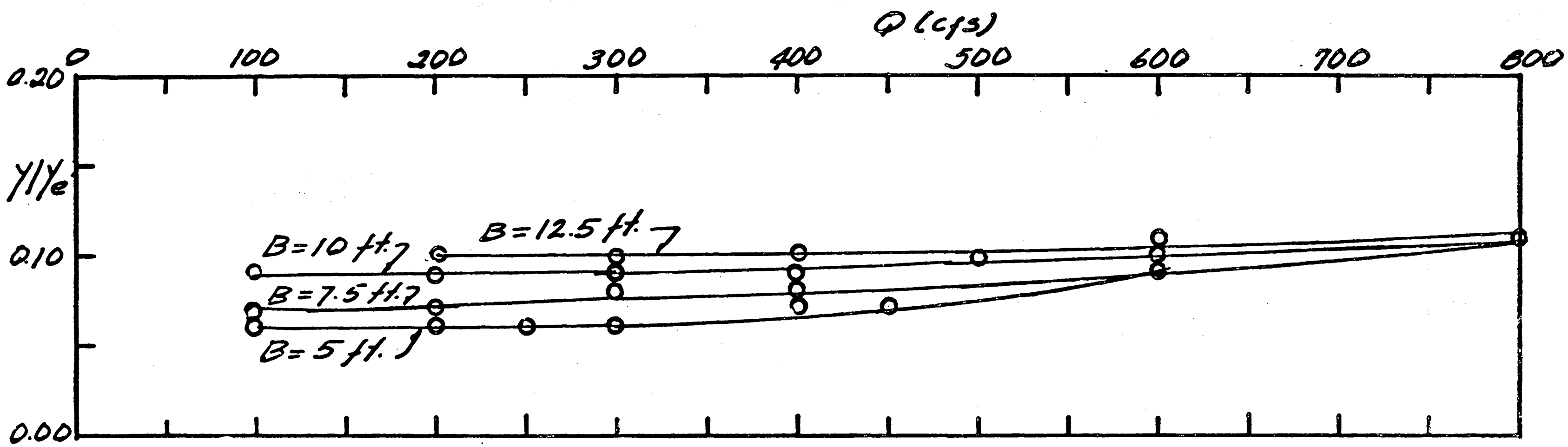

Fig 27.- Q vs Y/Ye for X/L=0.7 and D=8 ft.

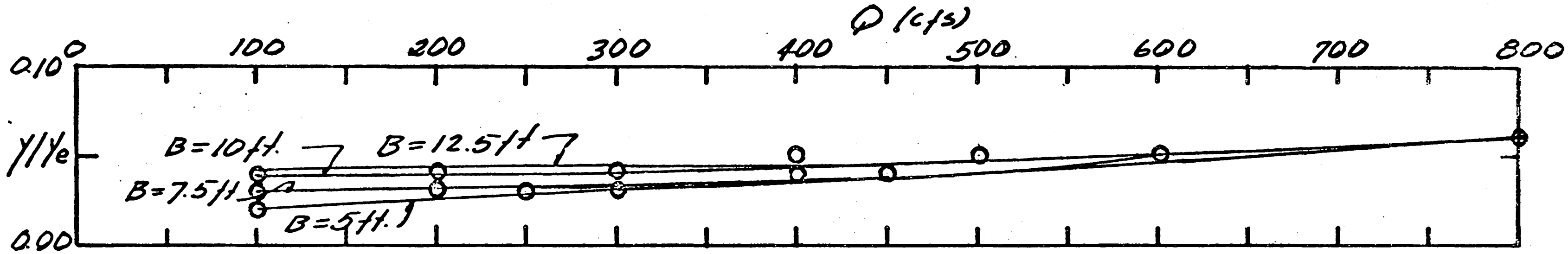

Fig 28. - Q vs y/ye for $x/L = 0.8$ and $D = 8$ ft.

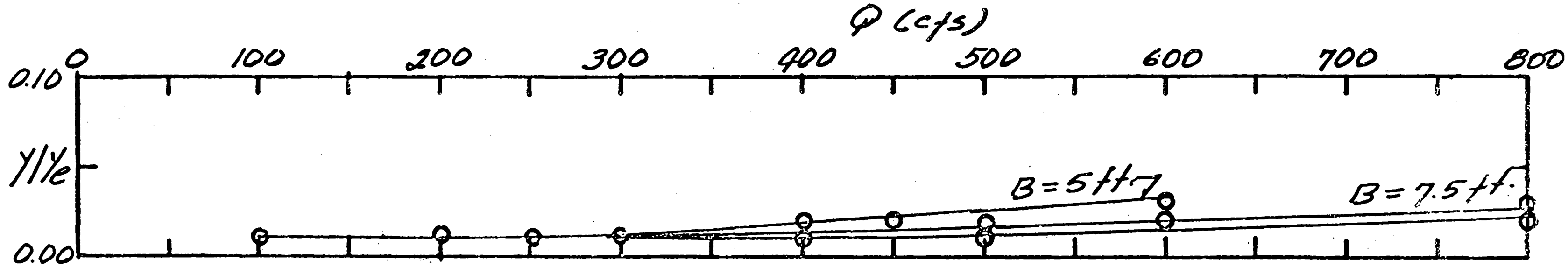

Fig 29. - Q vs y/ye for $x/L = 0.9$ and $D = 8$ ft.

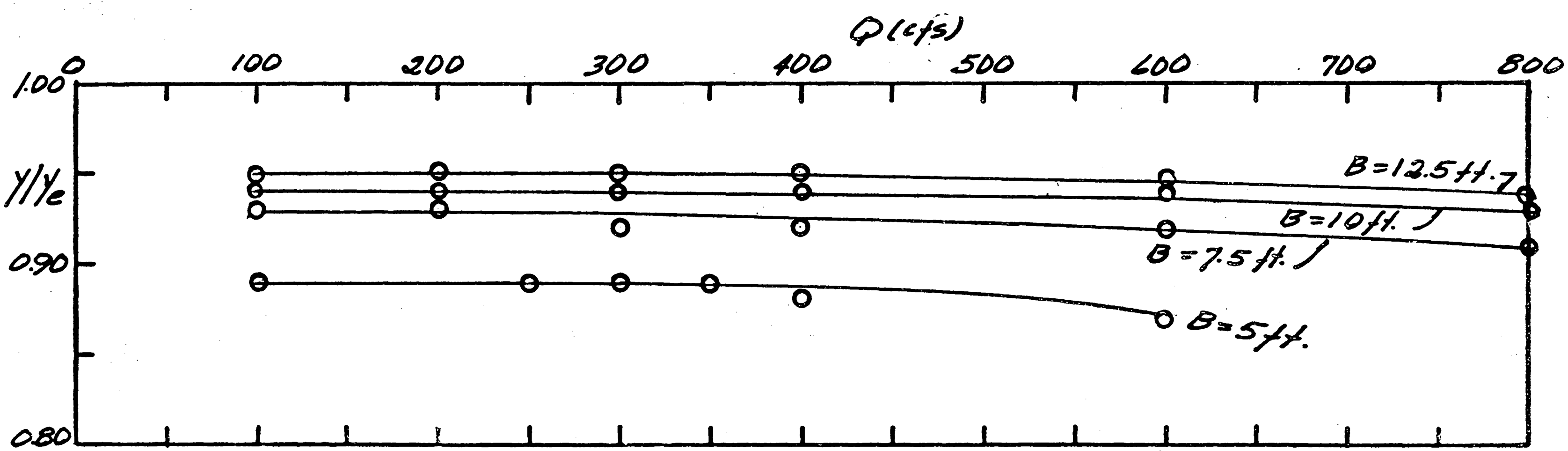

Fig 30. – Q vs Y/Ye for X/L = 0.1 and D = 10 ft

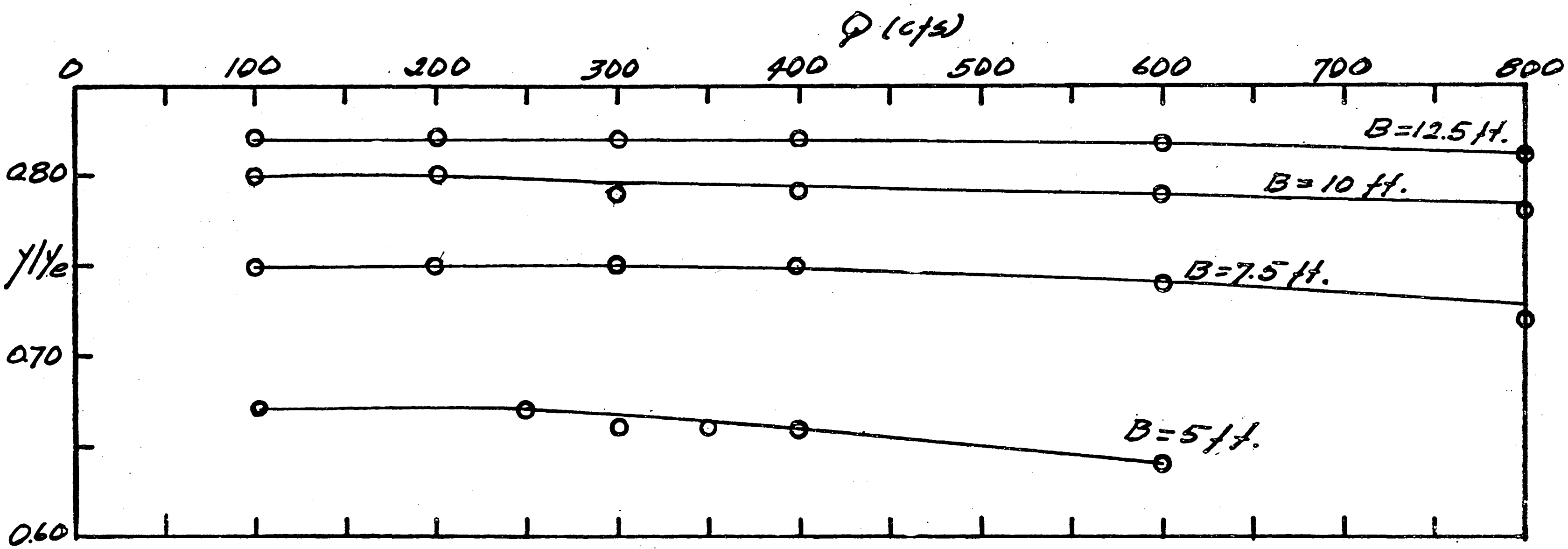

Fig 31.- Q vs y/ye for x/L=0.2 and D=10 ft.

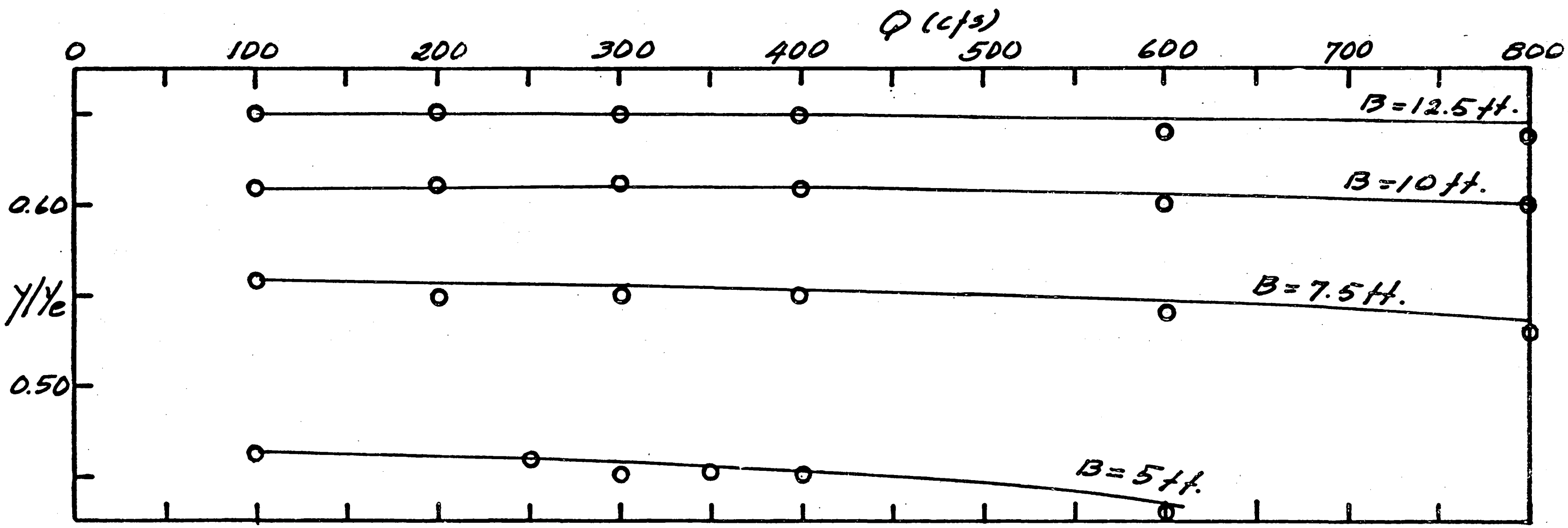

Fig 32. - Q vs Y/Ye for x/L = 0.3 and D = 10 ft.

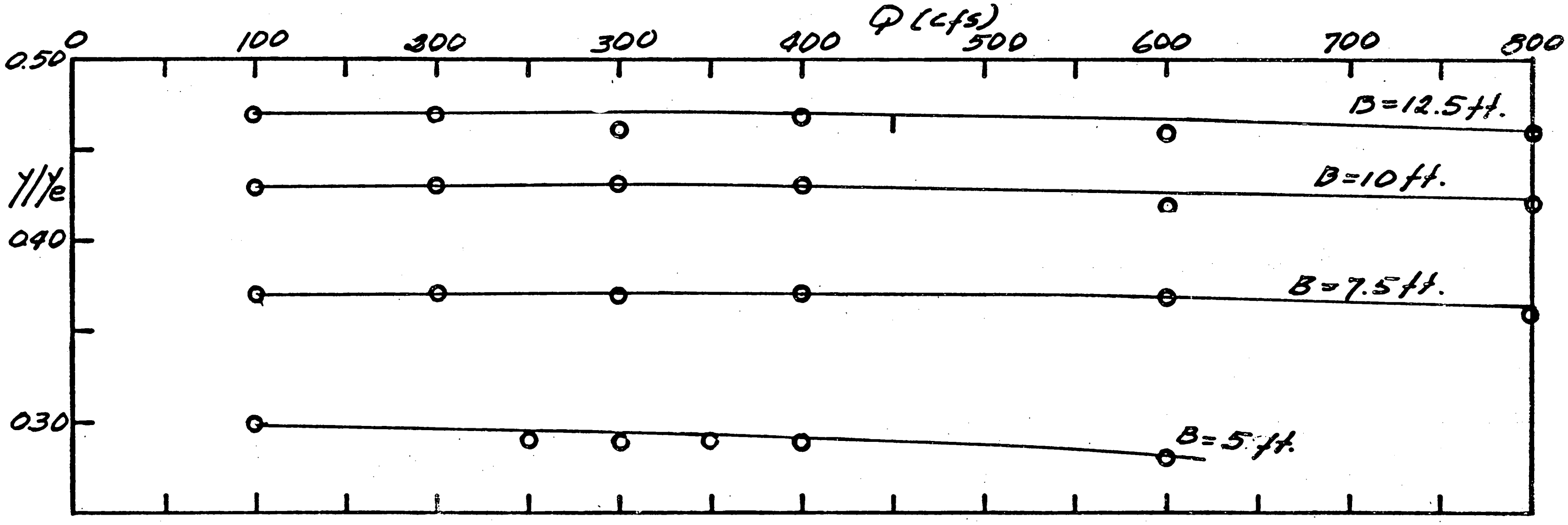

Fig 33. - Q vs Y/Ye for x/L = 0.4 and D = 10 ft.

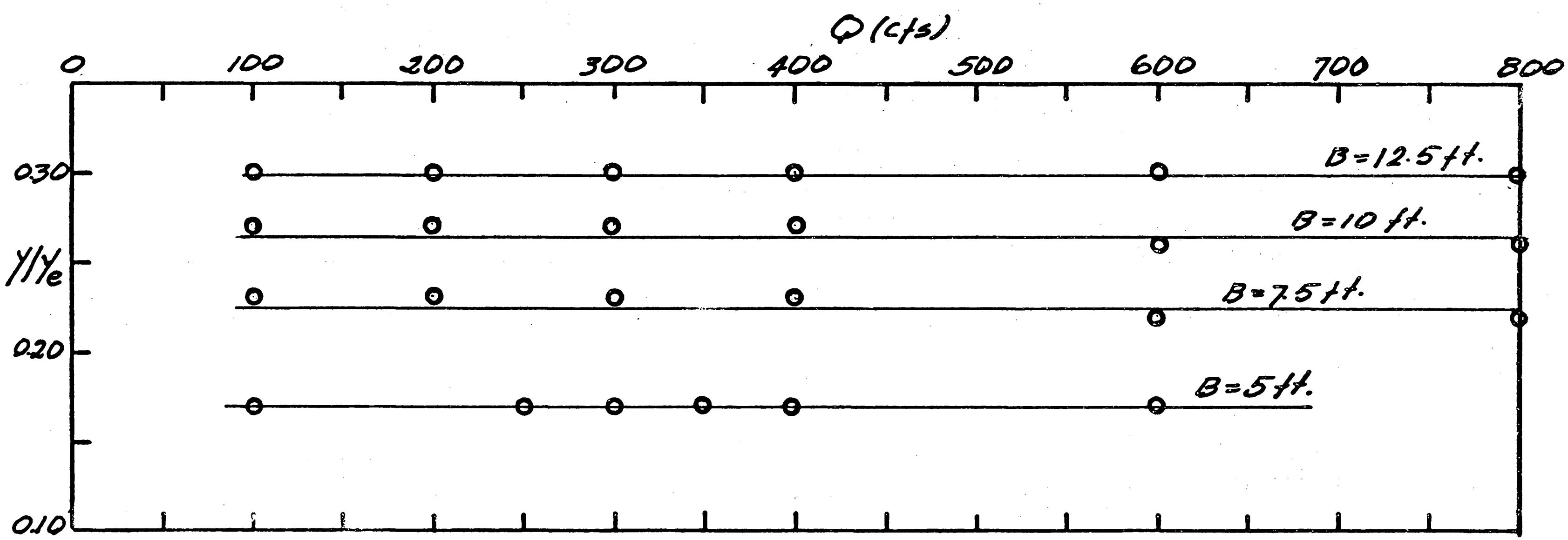

Fig 34. - Q vs Y/Ye for x/L = 0.5 and D=10ft

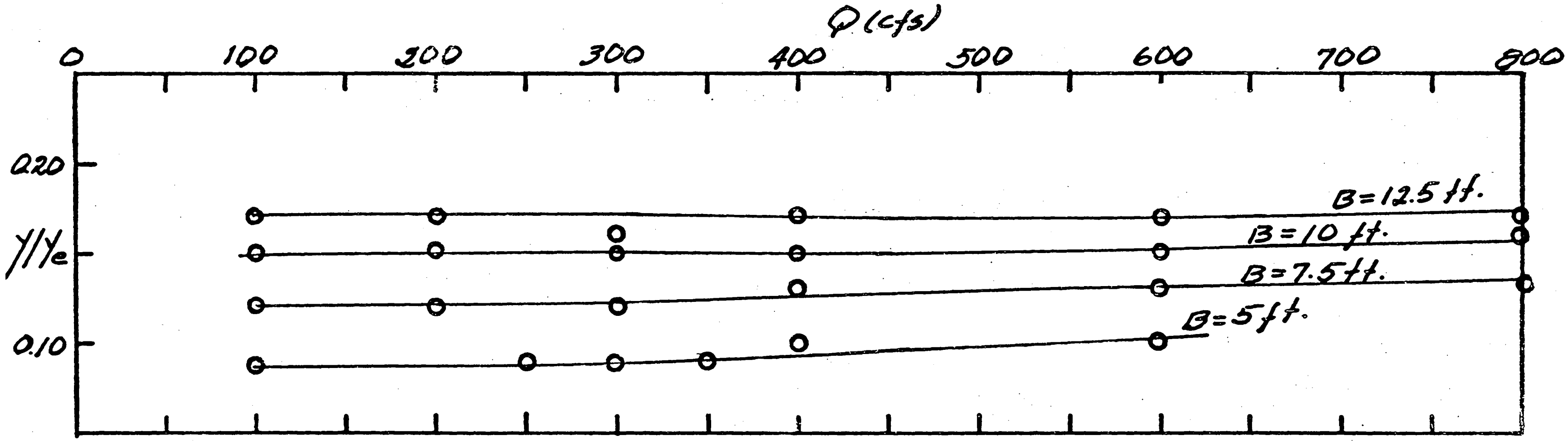

Fig 35.-Q vs Y/Ye for X/L = 0.6 and D=10 ft.

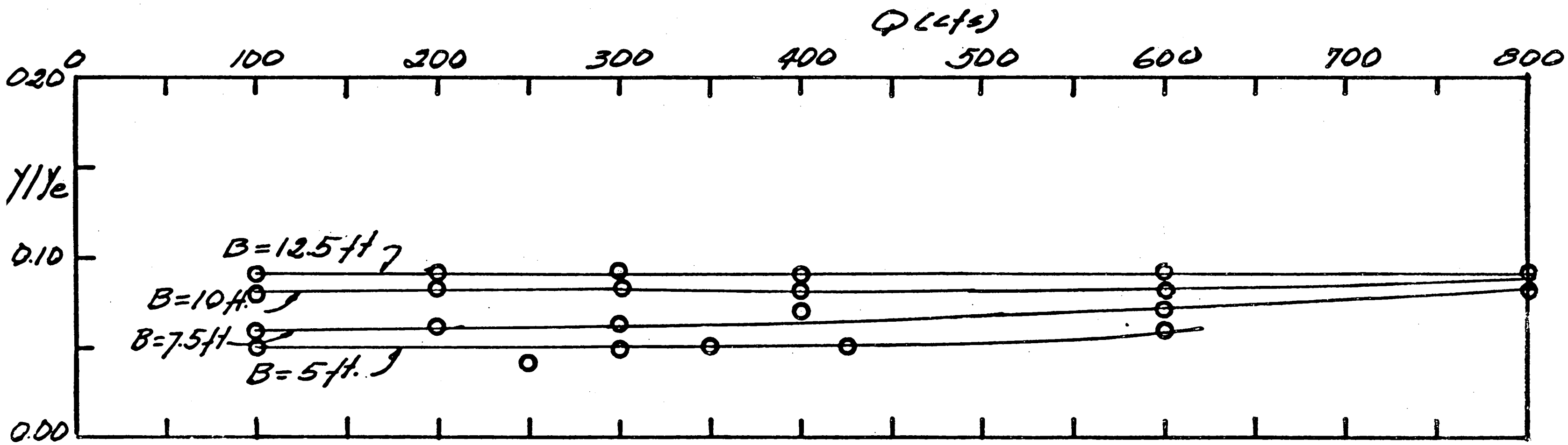

Fig 36. - Q vs Y/Ye for x/L = 0.7 and D = 10 ft

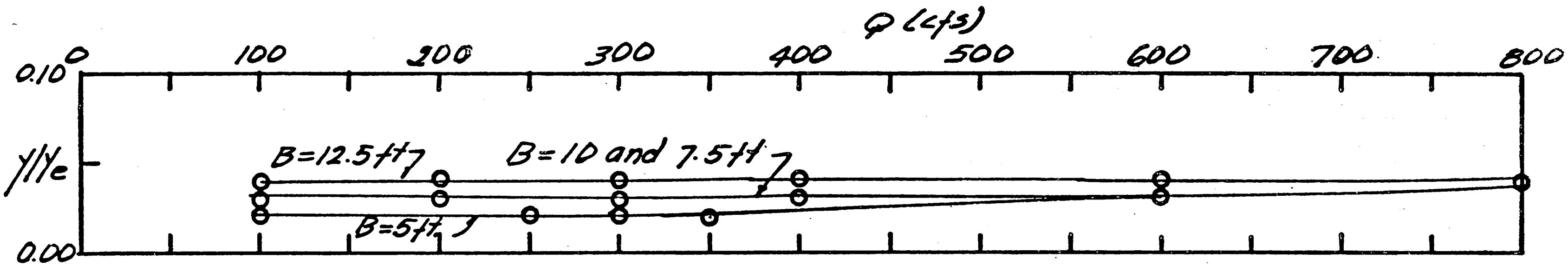

Fig 37. - Q vs Y/Ye for $x/L = 0.8$ and D=10 ft.

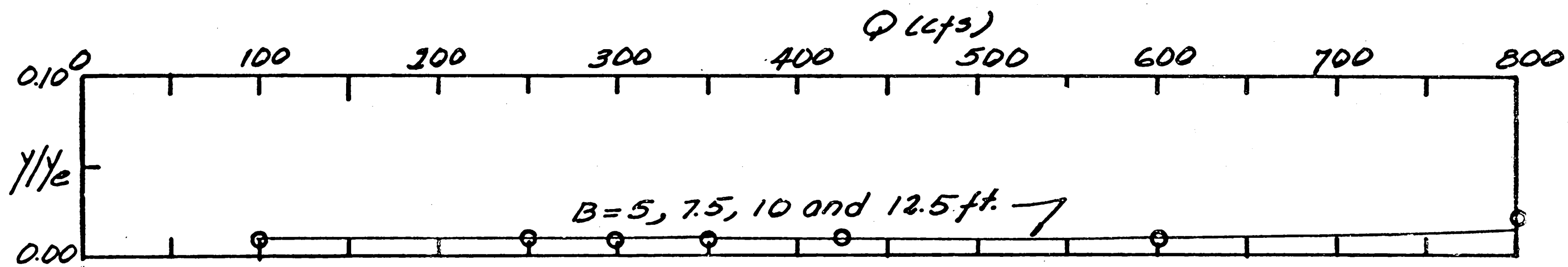

FIG 38. - Q vs Y/Ye for $x/L = 0.9$ and D=10 ft.

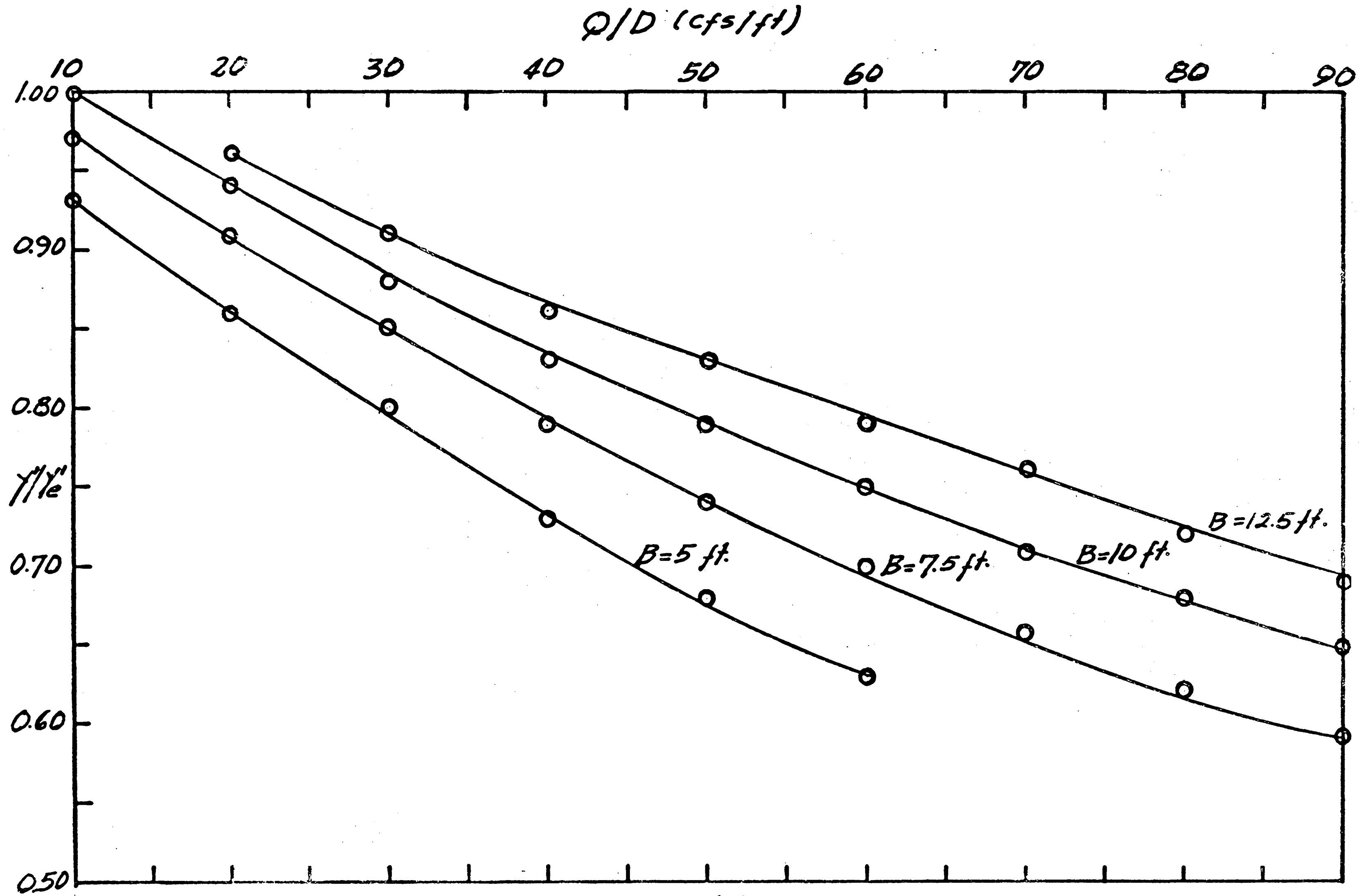

Fig 39.- Q/D vs Y'/Y'e for X/L = 0.1

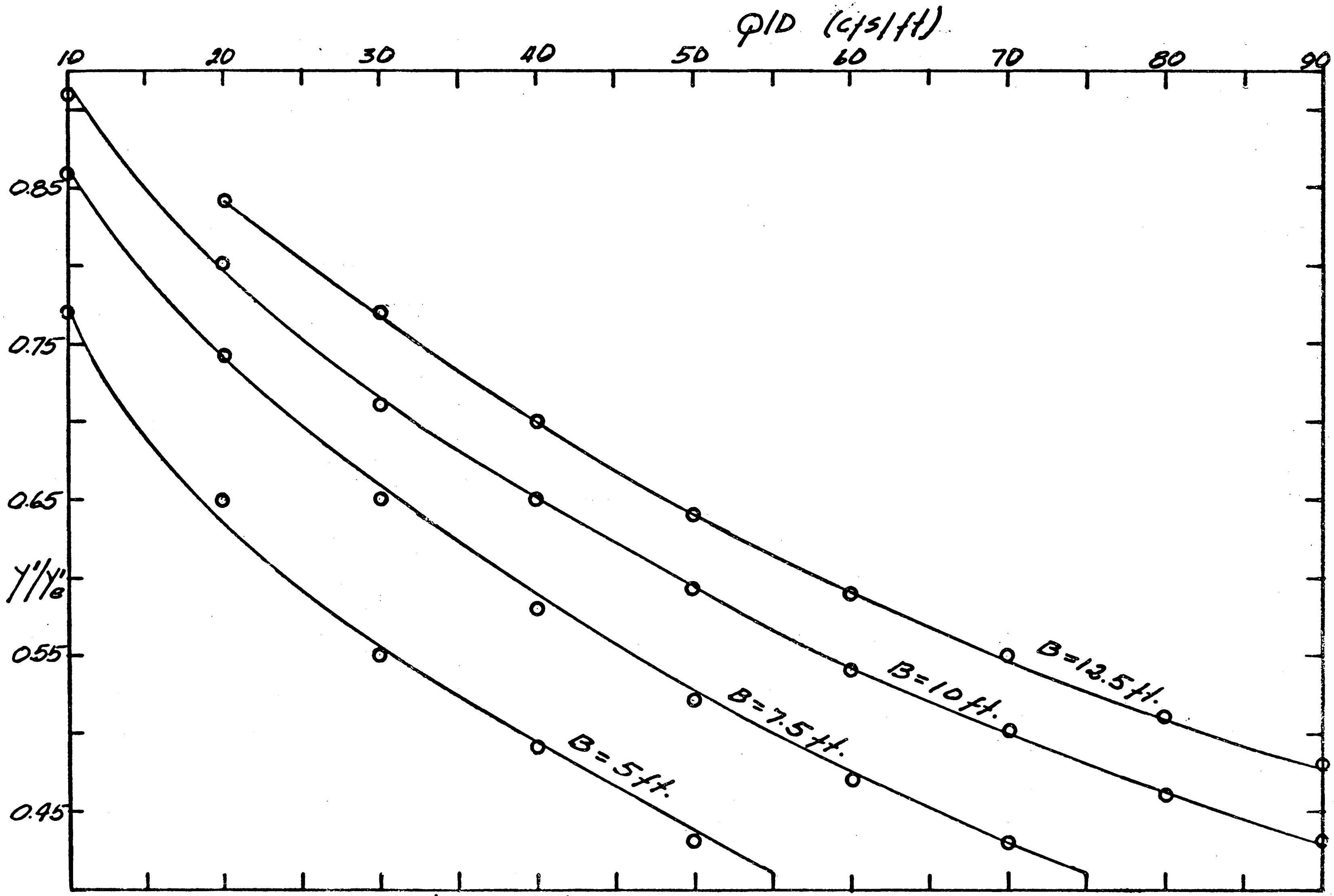

Fig 40. - Q/D vs y'/y'e for x/L = 0.2

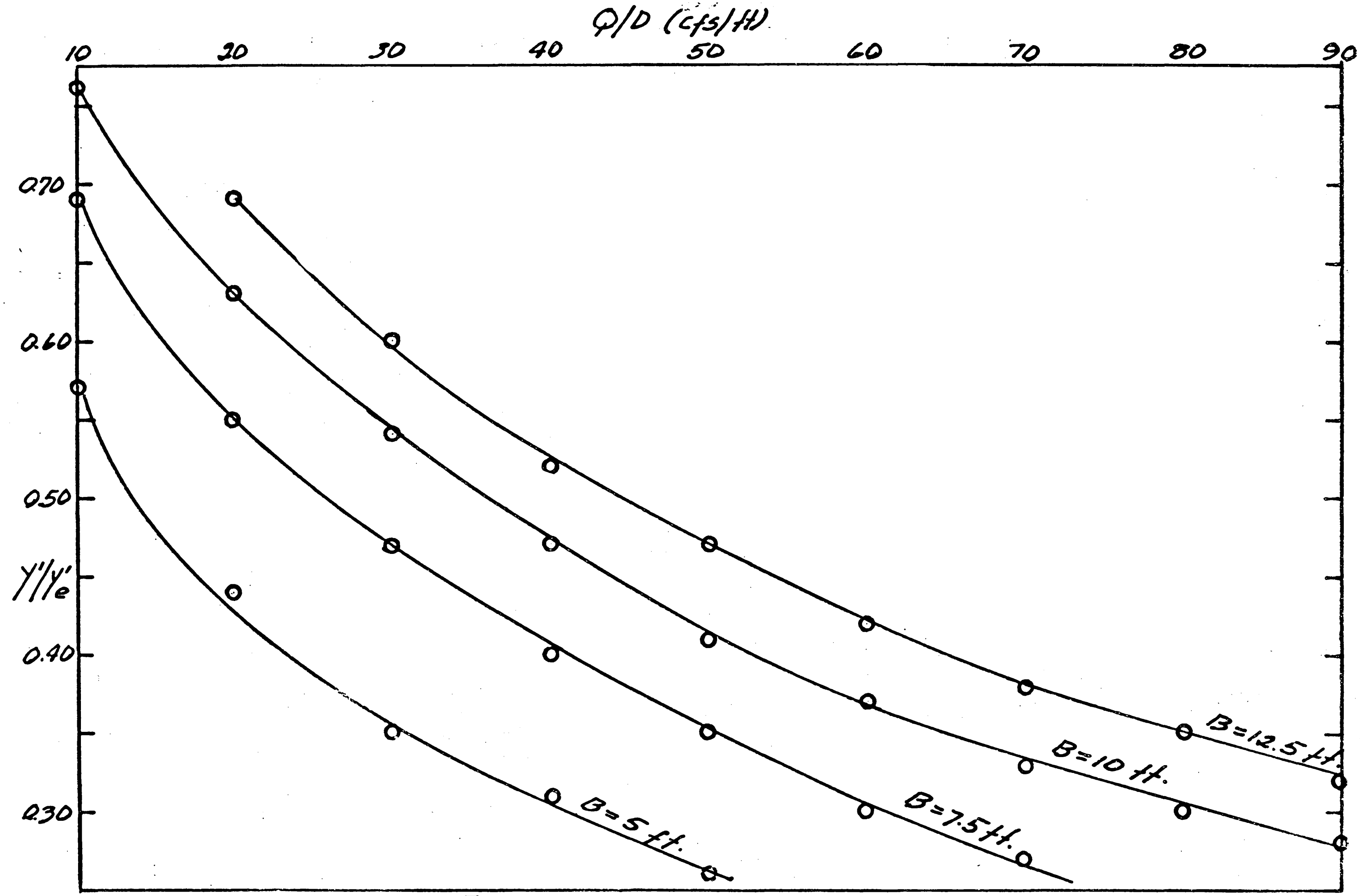

Fig 41. - Q/D vs y'/y'e for x/L = 0.3

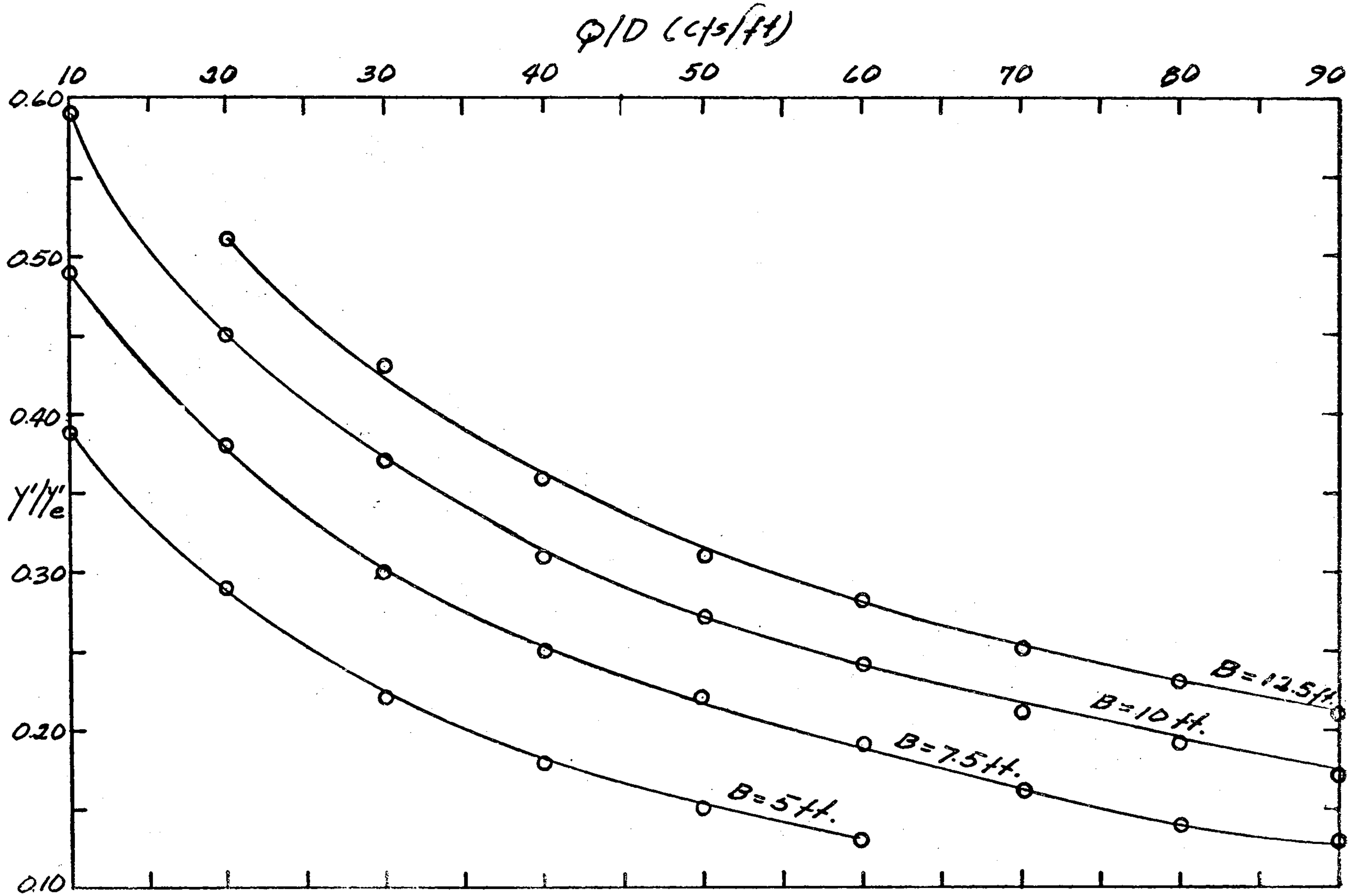

Fig 42.- Q/D vs Y'/Y'e for X/L=0.4

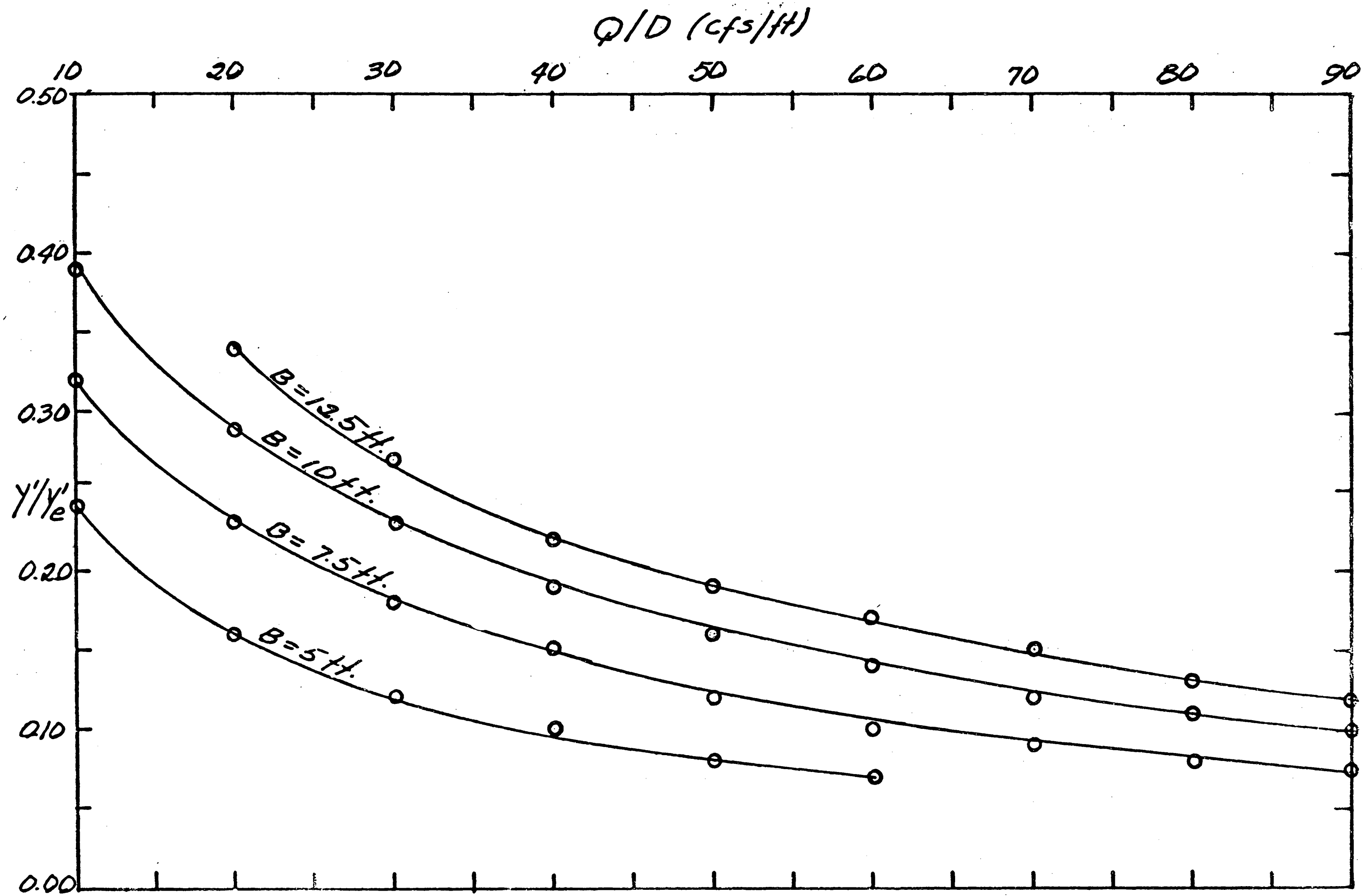

Fig 43. - Q/D vs y'/y'_e for $x/L = 0.5$

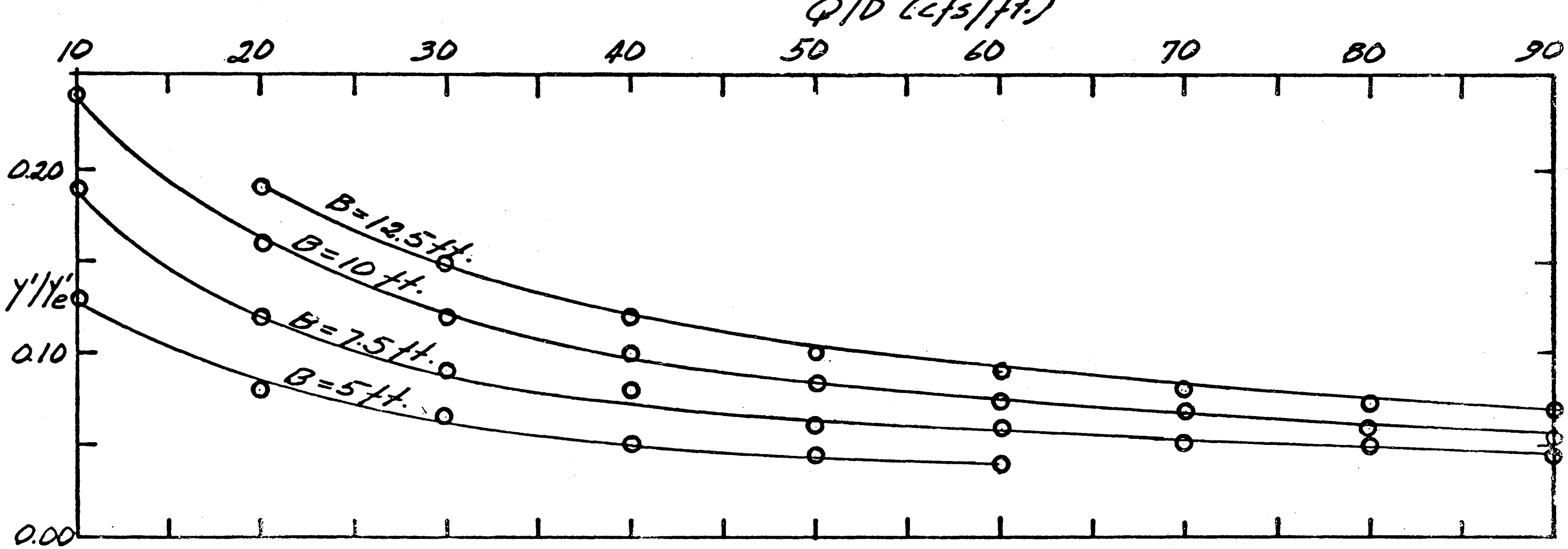

Fig 44. - Q/D vs Y'/Y'e for x/L = 0.6

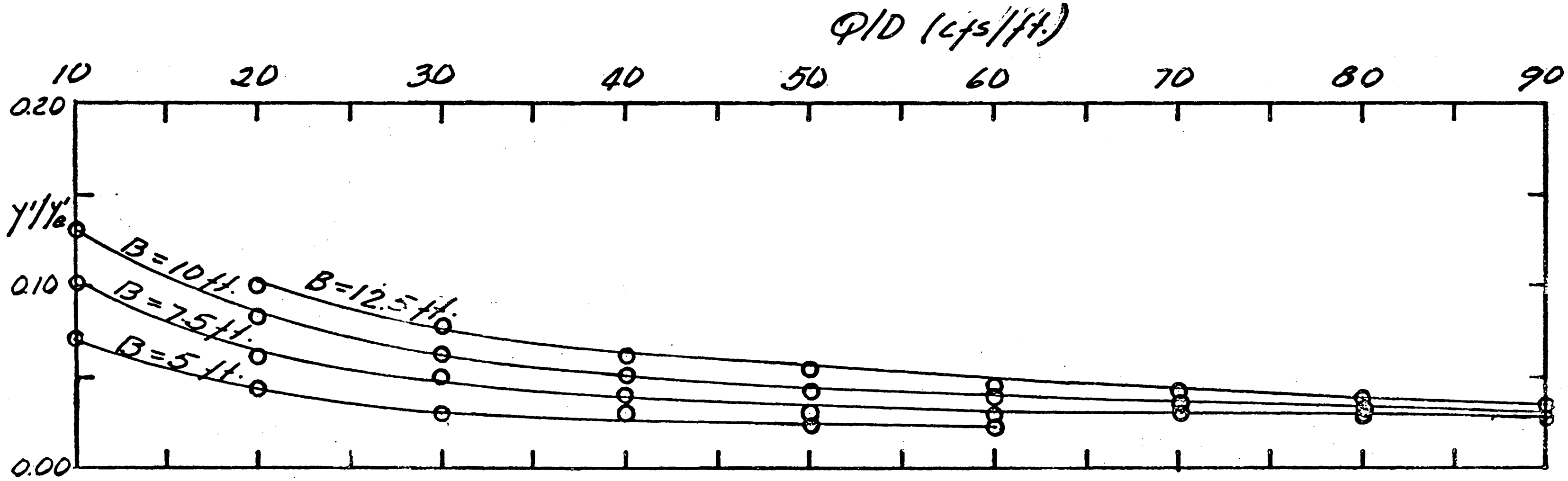

Fig 45. - Q/D vs Y'/Y'e for x/L = 0.7

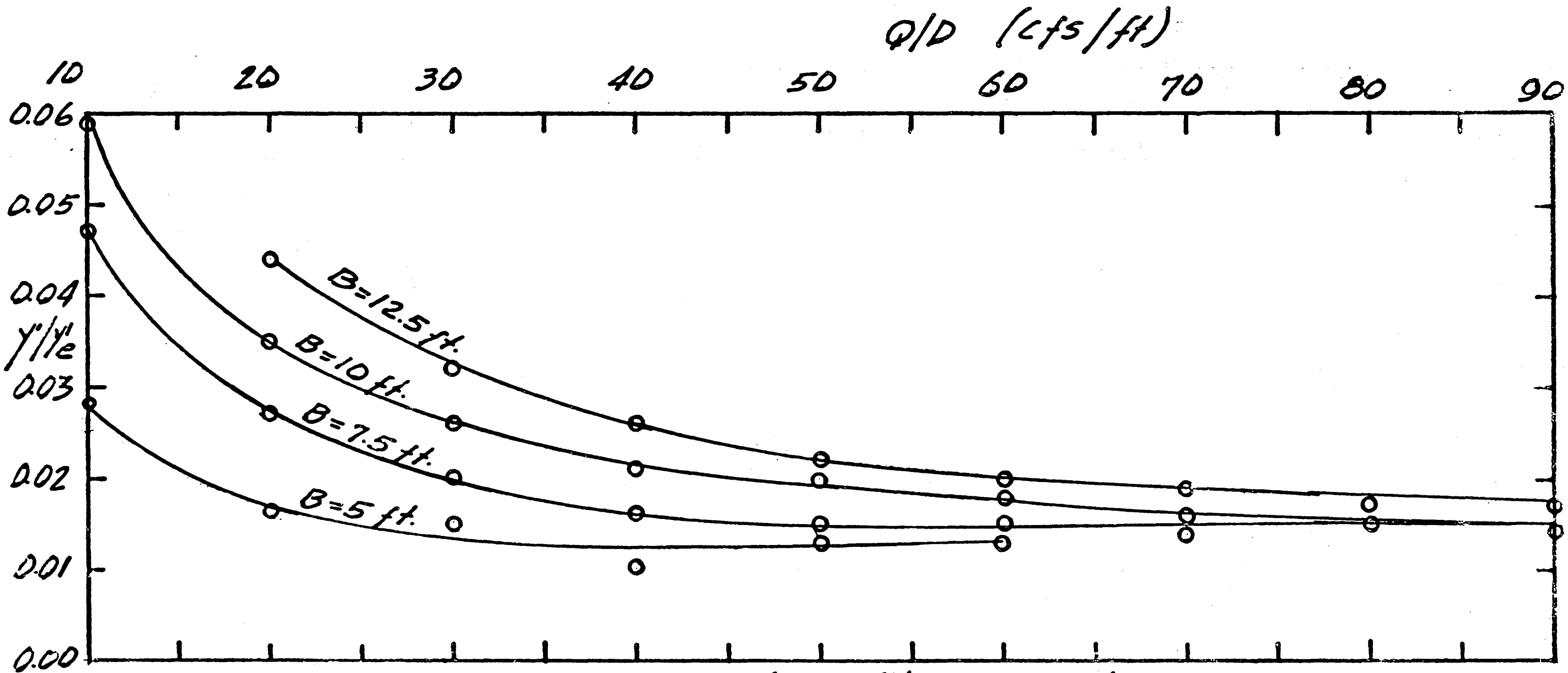

Fig 46.- Q/D vs Y'/Y'e for X/L=0.8

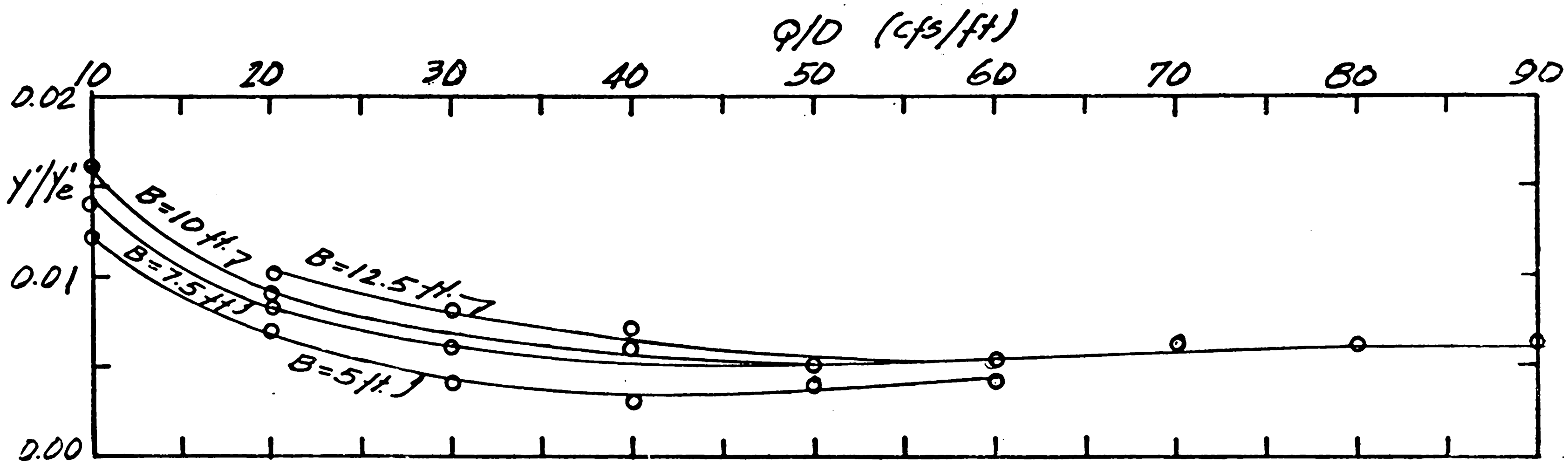

Fig 47. — Q/D vs Y'/Y'e for x/L = 0.9

ABSTRACT

Inlet transitions with sub-critical flow from trapezoidal to rectangular sections are studied. The water depths range from 5 to 10 feet and the bottom widths range from 5 to 12.5 feet. Graphs were constructed to design these types of transitions.

The behavior of a given transition with different discharges is also studied. It was found that more efficiency is gained when a given transition is used with a discharge greater than the design discharge, than when the transition is used with a discharge less than the design discharge.