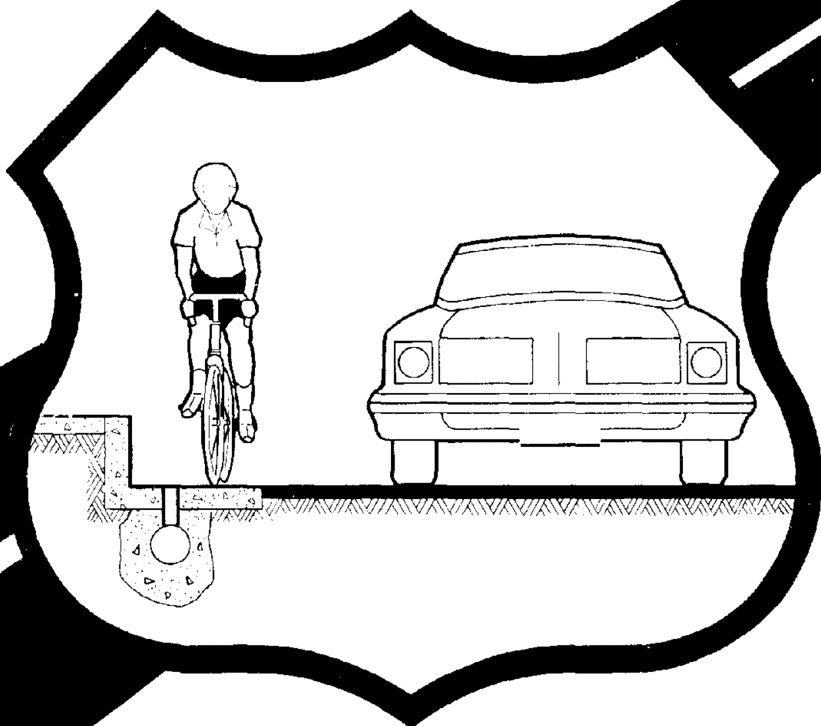
Report No. FHWA-RD-79-106

BICYCLE – SAFE GRATE INLETS STUDY

Vol. 4. Hydraulic Characteristics of Slotted Drain Inlets

February 1980

Final Report



Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

Prepared for

FEDERAL HIGHWAY ADMINISTRATION

Offices of Research & Development

Environmental Division

Washington, D.C. 20590

FOREWORD

This report describes the hydraulic tests conducted on slotted drain inlets. Tests were conducted to study the effect of individual parameters on the efficiency of slotted drains. Test results and design procedures are presented for 1.75 in. (44.45 mm) wide slots with solid vertical transverse spacers at 6 in. (152.4 mm) spacing, installed 3.5 in. (88.9 mm) from the curb face. They cover the total and partial flow interception conditions on continuous grades, and the sump condition. Both overland and gutter flow cases are studied.

The research was conducted by the Bureau of Reclamation's Engineering and Research Center for the Federal Highway Administration, Office of Research, Washington, D.C. under P.O. 5-3-0166. Subsequent reports will cover the general design procedures for slotted drain inlets.

Sufficient copies of this report are being distributed to provide a minimum of two copies to each FHWA Regional Office, one copy to each division office, and two copies to each State highway agency. Direct distribution is being made to the division offices.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

CONTENTS

Preceding page blank

CONTENTS - Continued

LIST OF FIGURES

LIST OF FIGURES - Continued

LIST OF FIGURES - Continued

LIST OF TABLES

ACKNOWLEDGEMENTS

This study was conducted by the USBR (U.S. Bureau of Reclamation) at their Engineering and Research Center, Denver, Colorado, for the Federal Highway Administration under Purchase Order No. 5-3-0166. The author would like to acknowledge the following individuals:

1. Philip Burgi - For his support and contributions as principal investigator during the first part of the study.

2. William Thompson, Robert Rubinson, Kathleen Houston, Carol De Angelis, Doug Staton, Jerry Fitzwater, Judy Kinkaid, Dan Mares, and Charles Cooper - For their contribution to hydraulic testing and data reduction.

3. Thomas Rhone and Danny King of the Hydraulics Branch - For their technical review and support.

4. Robert George and Richard McKisson - For their help with computer applications.

5. Dwight Reagan of the Texas Department of Highways and Public Transportation - For his ideas and contributions throughout the study.

6. Dr. D. C. Woo, Contract Manager, Environmental Design and Control Division, Federal Highway Administration - For monitoring the contract and his critical review and comments on research results.

The author would also like to acknowledge the laboratory shops, photographers, and other support groups at the Engineering and Research Center which contributed to this study.

NOTATION

Co = Orifice flow discharge coefficient
Cw = Weir flow discharge coefficient
E = Hydraulic efficiency (percent)
$\overline{E}$ = Average debris efficiency (percent)
g = Gravitational acceleration
L = Total flow capture length
LA = Actual slot length
n = Manning's roughness coefficient
P = Sheet flow manifold pressure
So = Longitudinal slope
Sx = Cross slope
q = Sheet flow
Q = Gutter flow
Qc = Carryover flow
Qi = Flow intercepted by the slot
T = Width of spread
W = Slot width
Y = Flow depth over slot
Z = Reciprocal of cross slope (Sx)

The standardized slot design symbol:

SV	- (S.W.)	- (S.S.)	- (C.D.)
Type of spacer	Width of slot opening	Spacing of spacers	Slot distance from curb

SM = Solid vertical spacer with gutter flow on smooth roadway surface

SV = Solid vertical spacer with gutter flow on rough roadway surface

DB = Double hexagonal bars with gutter flow on rough roadway surface

45 = Solid 45^{o} angle spacer with gutter flow on rough roadway surface

SV(SHEET-FL) = Solid vertical spacer with combined sheet and gutter flow on rough surface

CHAPTER 1

INTRODUCTION

The basic goal of the bicycle-safe grate inlets study is to investigate grate inlet designs which maximize bicycle and pedestrian safety as well as hydraulic efficiency and economy. This volume presents results of hydraulic and debris tests conducted on corrugated metal pipe slotted drain inlets. A slotted drain consists of a corrugated steel pipe cut along the longitudinal axis with a slot welded into the cut. When the drain is installed along a roadway, water falls through the slot and is carried to a collection point through the corrugated metal pipe. Typical slotted drain installations are shown in figure 1.

Bicycle and pedestrian safety and structural integrity for slotted drains were not analyzed. Volume 1(1)* can be referred to for safety characteristics of grate inlets with similar bar spacings. A study on the structural integrity of slotted drains is being done for the Federal Highway Administration by the California Department of Transportation. A report on the results of this study is scheduled for publication in the spring of 1980.

The main advantages of slotted drains are low cost, ease of installation, and efficiency.

Previous Studies

The first experimental study on slotted drain capacities was done in 1975 by In (2). In these tests, a 1:4 scale model was used to determine slot lengths required to capture 100 percent of the model flows from 0.02 to 0.17 ft^3/s (0.00057 to 0.0048 m^3/s). In's study resulted in linear log-log relationships for length of slot for total flow interception. In studied longitudinal slopes (S_o) of 1, 1.5, 2, 3, 4, 5, and 5.23 percent and cross slopes (S_x) of 2, 3, 4, and 5 percent.

Another study on slotted drain capacities was done by Masch (3) in 1978. These tests were done at full scale to relate slot capacities to other design parameters for slots-on-grade and slots-in-sags and to verify and extend In's data. Masch collected data for gutter slopes from 1 to 6 percent and cross slopes between 2 and 6 percent. The primary test measurement was slot length required for total flow interception for 1.75-inch-wide slots in a curb and gutter installation.

* Numbers in parenthesis refer to references at the end of the chapter.

The Texas Department of Highways and Public Transportation and the California Division of Highways have developed independent design procedures for slotted drains based on data available at the time the procedures were developed.

Purpose and Scope

The testing program for this study was designed to accomplish the following:

1. Determine slot lengths required for total flow interception for various (a) slot widths, (b) types of transverse bars, (c) distances from the slot to the curb face, and (d) roughness coefficients of the roadway surface.

2. Determine how much sheet flow slotted drains of different widths are capable of intercepting.

3. Determine the flow interception capacity of slots installed in a (vertical sag or) sump.

4. Investigate the tendency for slotted drains to clog with debris in different types of installations.

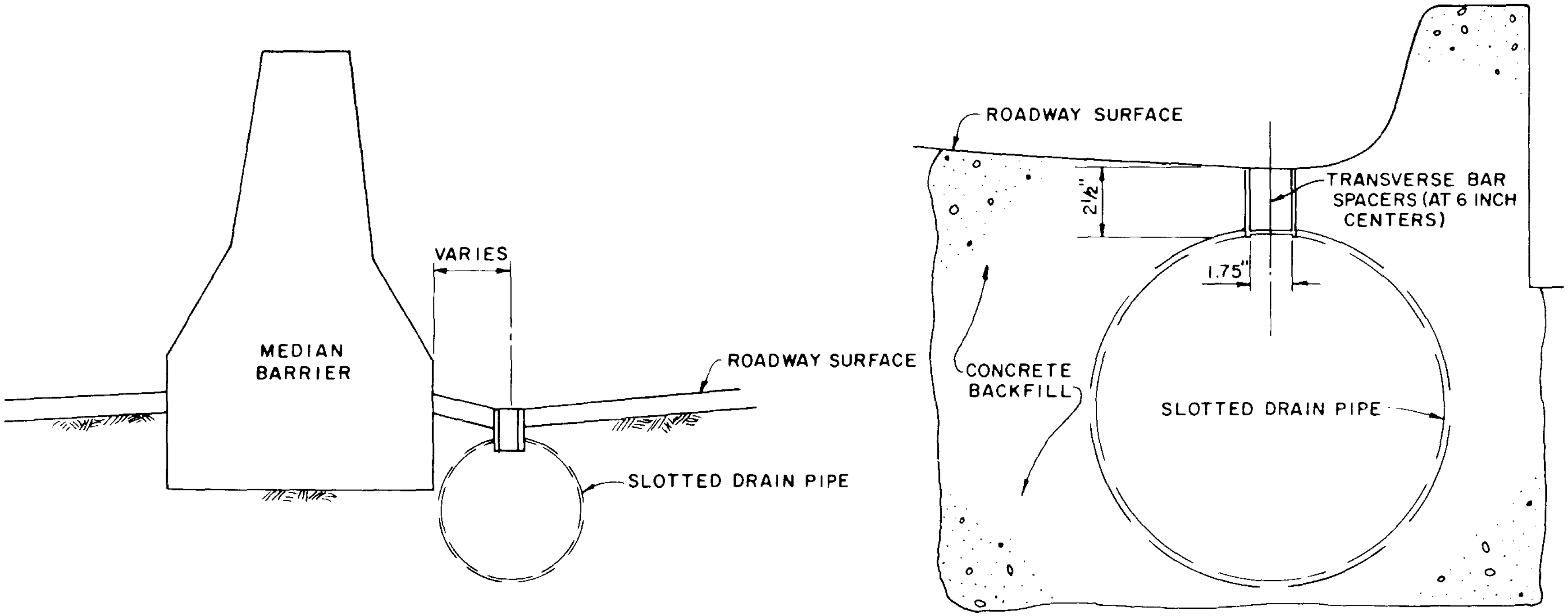
5. Determine the partial flow interception capability of selected types of slot when a portion of the flow is carried over to a downstream collection point.

References

(1) Burgi, P. H. and Gober, D. E., "Bicycle-safe Grate Inlet Study, Volume 1, Hydraulic and Safety Characteristics of Selected Grate Inlets on Continuous Grades," Federal Highway Administration, Report No. FHWA-RD-77-24, June 1977

(2) In, P.W.O., "Interception Capacity of Slotted Drain Pipe", MS Thesis Presented to California State University, Los Angeles, June 1975

(3) Masch, F. D., "Limited Capacity Studies on Armco Slotted Drain Pipe", Report to Armco Steel Corporation, January 1978



TYPICAL MEDIAN BARRIER SECTION

TYPICAL CURB AND GUTTER SECTION

Figure 1. - Typical slotted drain installations.
(1 inch = 25.4 mm)

CHAPTER 2

TEST FACILITY AND EXPERIMENTAL APPROACH

Test Facility

The test facility described in volume 1, chapter 5, was modified to accommodate the slotted drain study. The roadbed and curbs were removed from the facility and replaced with a roadbed with provisions for installing up to 56 ft (17.1 m) of slotted drain. A chute was also installed below the roadway to carry the flow intercepted by the slots to the laboratory sump. These modifications are shown in figure 2. Figure 3 shows the modified test facility. The rest of the test facility remained the same as described in volume 1 (1). The model is designed to achieve cross slopes (1/Z) from 0 to 1/16 and longitudinal slopes (So) of 0 to 9 percent. The gutter flow supply system is capable of supplying up to 5.3 ft^3/s (0.15 m^3/s).

Sheet Flow System

The test facility was also modified to supply sheet flow along the length of the roadway (see fig. 4). The sheet flow system is made up of nine 6-ft-long manifolds. Water is supplied through 2-in (50.8-mm) pipe with 1/4-in (6.3-mm) diameter holes at 3-in (76.2-mm) spacing. The holes are directed down onto the roadway to dispurse the flow. The pressure in each manifold is regulated separately with valves to obtain equal pressure; thus obtaining uniform flow. Figure 4 shows the sheet flow supply system. A separate pressure versus flow calibration was done for each manifold. Pressure was measured with 0 to 30 lb/in^2 (0 to 200 kPa) pressure gages. Flow was measured with a 90 degree V-notch wier (described in volume 1). The following equation relates sheet flow, q in ft^3/s per ft to manifold pressure, P in kPa in the flow range from 0.01 to 0.04 ft^3/s per ft (0.086 to 0.345 L/s per m).

$$q = 0.023 \log_{10} P - 0.011 \qquad (2\text{-}1)$$

Flows calculated with this equation are accurate within ± 5 percent. For tests using sheet flow, pressures in each manifold were adjusted to a constant value, thus obtaining uniform sheet flow.

Slot in a Sump Condition

In order to test flow depths up to 10 in (0.254 m), a scale model was used. A 1-in (25.4-mm) wide slot was used, making the scale ratio 1:1.75 for a 1.75-in (44.45-mm) prototype width. An 8-in (203-mm) high barrier was installed across the roadway about 35 ft (10.7 m) downstream from the headbox. The slots were installed just upstream from the barrier, causing all the flow to go through the slot. Figure 5 shows the test setup for the sump condition.

Roadway Roughness

To determine the roadway roughness the slot was covered and the roadway cross slope was set horizontal, forming a rectangular cross section. Depth measurements were made at 3-in (76.20-mm) intervals across the 7-ft (2.13-m) roadway, 36 ft (11.9m) from the headbox. Tests were conducted at slopes, So = 1, 2, and 4 percent and at discharges of 2, 3, and 4 ft^3/s (0.057, 0.085, and 0.113 m^3s). Manning's equation was used to determine the "n" value. Figure 6 shows a roughness test.

The initial tests were done on a smooth roadway surface. The Permaply roadbed was painted with epoxy paint. The Manning's "n" measured for this surface ranged from 0.0087 to 0.0093, averaging 0.009. The roughness coefficient used for the majority of the tests was, n = 0.0165. The surface was treated with sand and marine varnish in the same manner described in volume 1 to roughen the surface. Surface roughness tests were then repeated to assure that the "n" value was between 0.016 and 0.017.

Experimental Approach

Tests were conducted to study the effect of changing individual parameters on the 100 percent flow capture lengths for various slotted drain designs. The parameters studied inculde:

1. Roadway roughness
2. Slot width
3. Distance from curb to slot
4. Type of transverse spacer bar
5. Slope conditions
6. Combined sheet flow and gutter flow

Figure 7 is a definition sketch for the variables involved. Table 1 lists the test conditions for 100 percent gutter flow capture. An average of 5 discharges were tested for each slope condition. In addition to the tests listed in table 1 for 100 percent gutter flow capture, tests were also conducted to investigate the following:

(1) The sheet flow interception capability of slotted drains. - Drains

with solid vertical transverse bars at 6-in (152.4-mm) spacing were used. Slot widths of 1.00-in (25.4-mm), 1.75-in (44.45-mm), and 2.5-in (63.5-mm) were studied at cross slopes of 1/16, 1/24, and 1/48, and longitudinal slopes of 1/2, 1, 2, 4, 6, and 9 percent.

(2) The partial flow interception capability of a selected slot configuration. - A 1.75-in (44.45-mm) wide slot with solid transverse bars at 6-in (152.4-mm) spacing with the curb face 3.5 in (88.9 mm) from the slot centerline (SV-1.75-6-3.5) was selected for these tests.

Partial flow interception was measured for slot lengths of 8, 16, 24, and 32 ft (2.43, 4.87, 7.30 and 9.73 m. Cross slopes of 1/16, 1/24, and 1/48 were tested at longitudinal slopes of 1/2, 1, 2, 4, 6, and 9 percent for each slot length.

(3) The interception capacity of slotted drain sump condition. - A 1:1.75 scale was used to test SV-1.75-6-3.5 (prototype scale) slots. All three cross slopes (Z = 16, 24, and 48) were tested at So = 0.2 percent, for 4-, 8-, and 12-ft (1.22-, 2.44-, and 3.66-m) prototype lengths.

Hydraulic Tests

The typical test procedure was to install a selected slot type and length in a particular physical setup and record several parameters over a range of flow and slope conditions. For each slope condition, 4 or 5 discharges were tested. The maximum gutter flow was limited by the system capacity, 5.3 ft^3/s (0.15 m^3/s) or the length of the slot. Figure 8 shows a typical test.

Total flow interception measurements included:

1. Gutter flow (Q) - Measured with a combination Venturi-orifice meter described in chapter 5 of volume 1
2. Total flow interception length (L)
3. Width of spread (T) measured just upstream of the slot
4. Depth of flow measured 1 ft (0.305 m) upstream of the slot

For tests where a portion of the flow was not captured by the slot, the bypass flow was measured with a 2-ft (0.61-m) wide contracted weir or a 90° V-notch weir, depending on the flow rate. These weirs are described in chapter 5 of volume 1. For tests including sheet flow, the manifold pressures were set for a specified sheet flow and recorded.

Flow entering the roadway from the headbox was controlled with a variable width sluice gate. The adjustable sluice gate made it possible to build up head in the headbox and control the width of spread and depth of flow entering the roadway. With the gate properly adjusted, a minimum roadway length was required to establish uniform flow. A series of tests were conducted to determine the length of upstream approach needed to establish uniform flow. With sluice gate control, a 10-ft (3.05-m) approach was adequate. The approach length used for most of the tests was 11 ft (3.4 m). Without the sluice gate, up to 35 ft (10 m) of approach was needed to establish uniform flow.

Debris Tests

The tendency for different slots to clog with debris was investigated for all physical conditions listed in table 1 with the exception of the smooth road tests. The debris tests were conducted to provide a method for comparing the relative debris handling capability of the various types of slotted drains. The tests were similar to those described in volume 1, chapter 5. One hundred fifty pieces of 3- by 4-in (76- by 102-mm) brown craft paper were saturated and scattered in a 2-ft (0.6-m) wide area with 50 pieces upstream from and 100 pieces beside the slotted drain (fig. 9). Flow was steadily increased over a 5-minute period to a constant discharge and held for another 5 minutes. Debris which failed to move naturally was loosened from the road surface and allowed to move to the slot. After each test, debris which did not pass through the slot were retrieved and counted.

Debris tests were conducted at longitudinal slopes of 1/2 and 4 percent and cross slopes of 1/16 and 1/48. Each test was repeated 3 times to ensure consistency. In the sump condition, debris tests were conducted for all slot lengths and all slope conditions using 1.71- by 2.29-in (43.4- by 58.2-mm) debris to simulate 3- by 4-in (76.2- by 101.6-mm) prototype size. Figure 10 shows debris on the roadway prior to a vertical sump debris test. The debris handling efficiency ($\overline{E}$) is defined as the percentage of the total debris passing through the slot.

Each hydraulic and debris test was photographed and observations were recorded to complete the documentation.

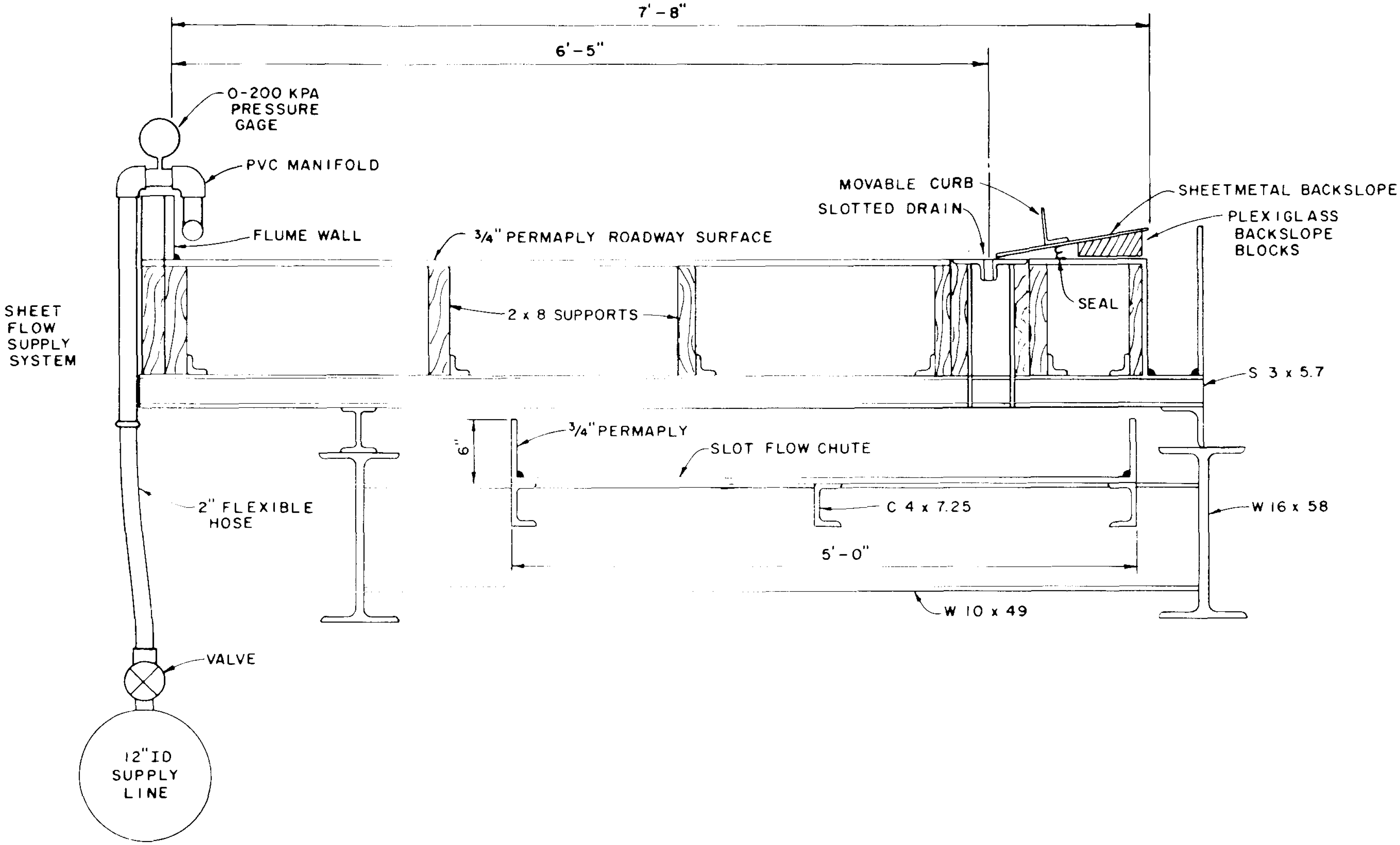
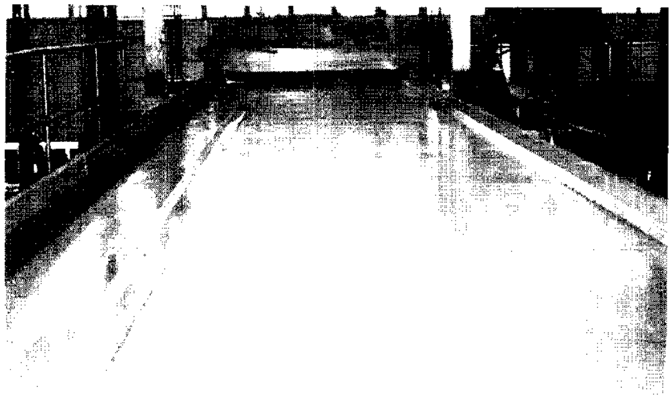
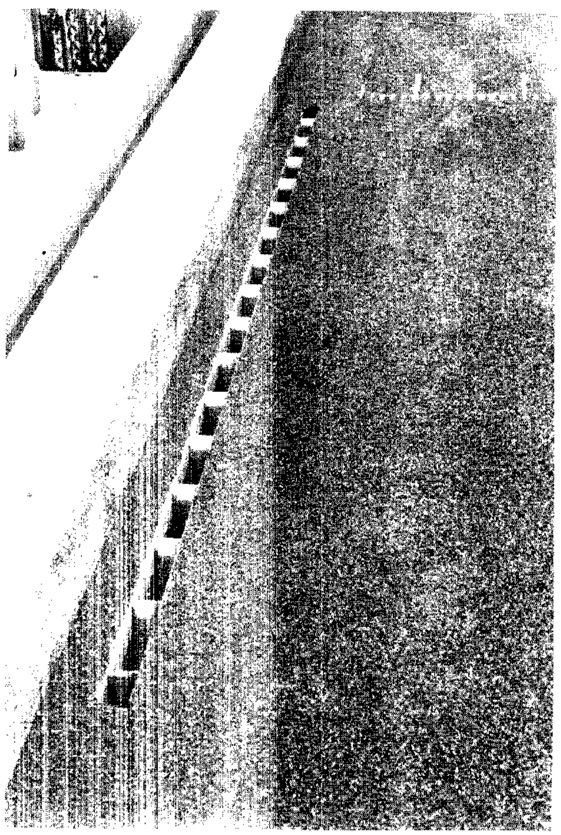


Figure 2. - Section through model roadbed showing modifications for slotted drain study (1 inch = 25.4 mm, 1 foot = 0.3048 m).

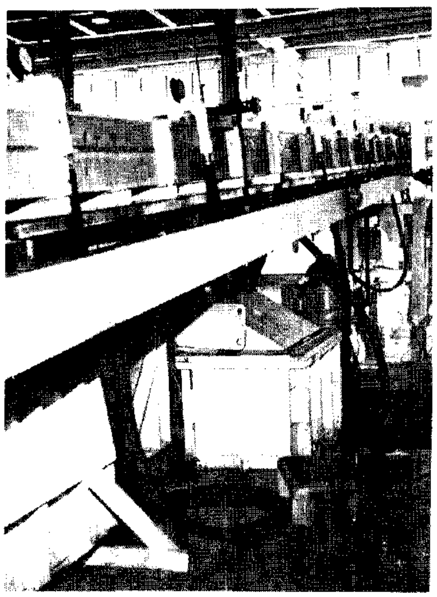


a. Smooth roadway surface with 7 - 8-ft (2.44-m) slot sections being installed.

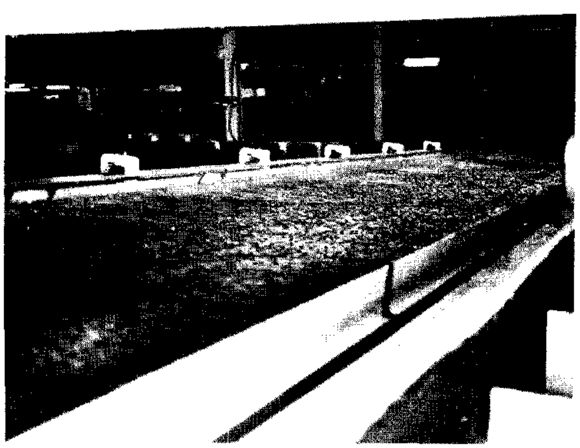


b. Test setup with rough roadway. One 8-ft (2.44-m) section is open. The curb face is 3.50 in (88.9 mm) from the centerline of the slot.

Figure 3. - Model roadway for slotted drain tests.



a. Sheet flow supply system.



b. 1/4-inch-diameter holes in longitudinal pipe direct water down to disperse the flow.

Figure 4. - Sheet flow supply system.

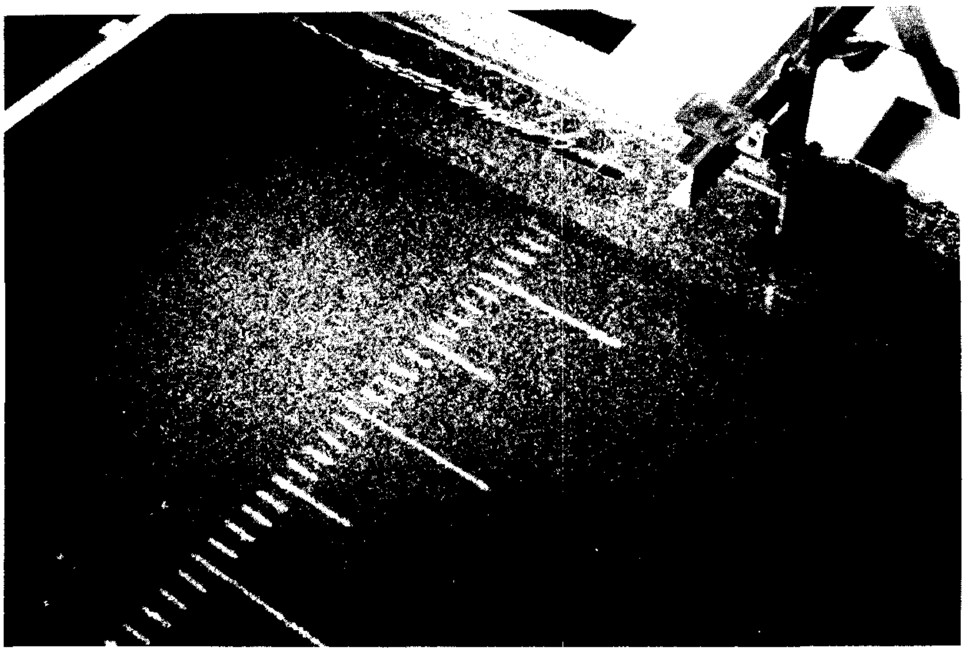


Figure 5. - Test setup for sump test. (Z = 48, Q = 0.61 ft^3/s (0.017 m^3/s), Y = 0.195 ft (0.059 m)

Figure 6. - Manning's n roughness test, smooth roadway surface. (Note point gage for water surface measurement at right.)

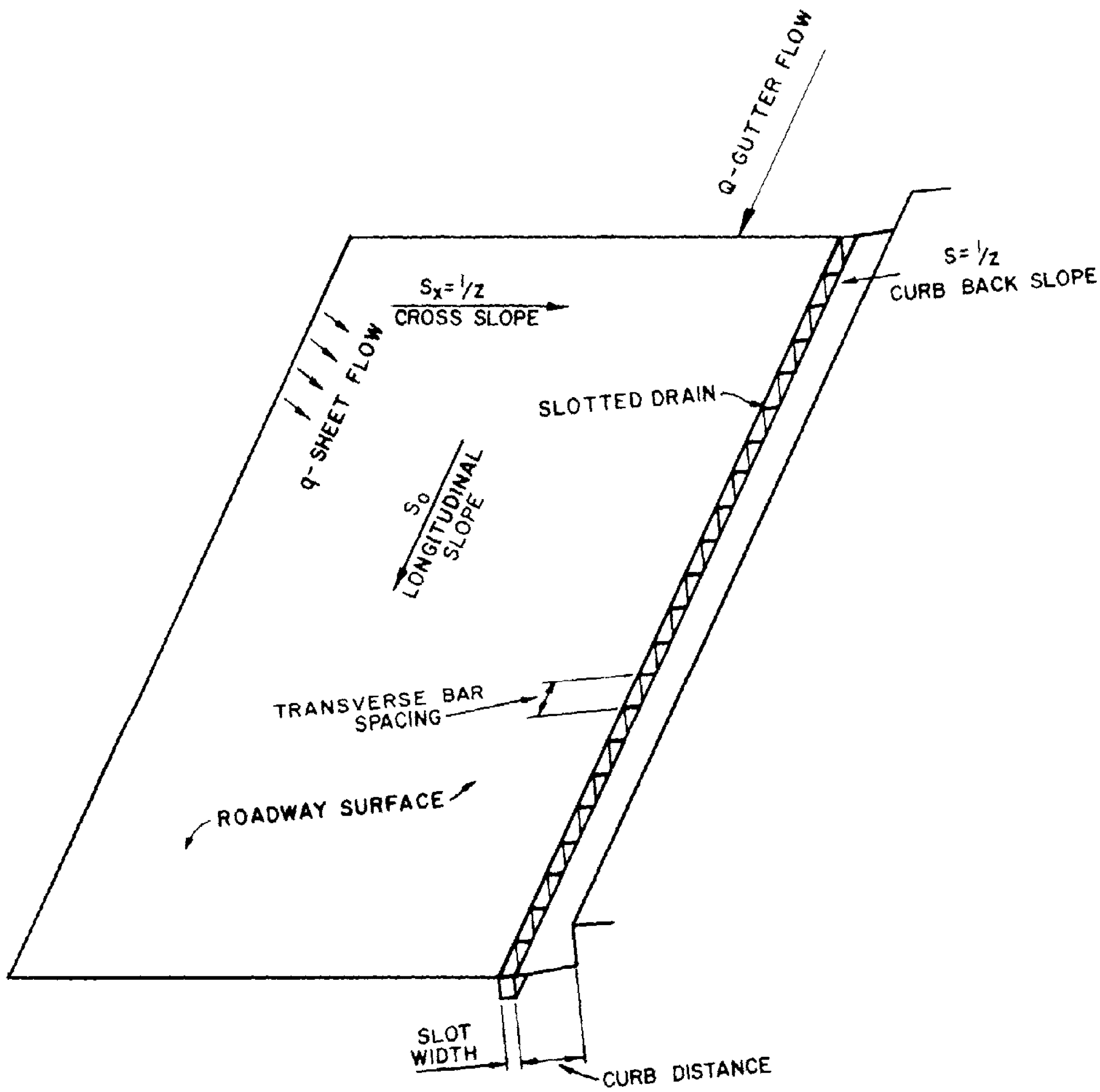


Figure 7. - Test setup for total flow capture tests.

Table 1. - Test conditions for 100 percent gutter flow capture tests

Roadway Roughness	Slot width	Curb * distance	Type of transverse bar	Cross ** slopes (Z)	Longitudinal slopes (S_0) %
Manning's "n" = 0.0165	2.50 in (63.5 mm)	3.50 in (88.9 mm)	Solid vertical at 6-in spacing (152.4 mm)	16	2 4 6 9
				24	2 4 6 9
				48	2 4 6 9
	1.00 in (25.4 mm)			16	1/2 2 4 6 9
				24	2 4 6 9
				48	1/2 2 4 6 9
	1.75 in (44.45 mm)		Double hexagonal at 6-in spacing (152.4 mm)	16	2 4 6 9
				24	2 4 6 9
				48	2 4 6 9
			Double hexagonal at 4-in spacing (101.6 mm)	16	2 4 6 9
				24	2 4 6 9
				48	2 4 6 9
			Solid 45° angle at 6-in spacing (152.4 mm)	16	2 4 6 9
				24	2 4 6 9
				48	2 4 6 9
			Solid vertical + at 4-in spacing (101.6 mm)	16	2 4 6 9
				24	2 4 6 9
				48	2 4 6 9
			Solid vertical + at 6-in spacing (152.4 mm)	16	1/2 2 4 6 9
				24	2 4 6 9
				48	1/2 2 4 6 9
		0 in (0 mm)	Solid vertical + at 6-in spacing (152.4 mm)	16	1/2 1 2 4 6 9
				24	1/2 1 2 4 6 9
				48	1/2 1 2 4 6 9
		7 in (177.8 mm)	Solid vertical + at 6-in spacing (152.4 mm)	16	1/2 2 6
				48	1/2 2 6
Manning's "n" = 0.009	1.75 in (44.45 mm)	3.50 in (88.9 mm)	Solid vertical + at 6-in spacing (152.4 mm)	16	1/2 1 2 4 6 9
				24	1/2 1 2 4 6 9
				48	1/2 1 2 4 6 9
		0 in (0 mm)	Solid vertical + at 6-in spacing (152.4 mm)	16	1/2 1 2 4 6 9
				24	1/2 1 2 4 6 9
				48	1/2 1 2 4 6 9

* Curb distance - The distance from the curb face to the curb edge of the slot.
** Cross slope = 1/Z

Notes: Debris tests were also conducted for all slots tested at cross slopes of 1/16 and 1/48 and longitudinal slopes of 1/2 percent and 4 percent.

\+ Tests were also conducted on a 1.75-in (44.45-mm) wide slot with solid vertical bars at 6-in (152.4-mm) spacing using combined gutter flow and sheet flow at all slopes.

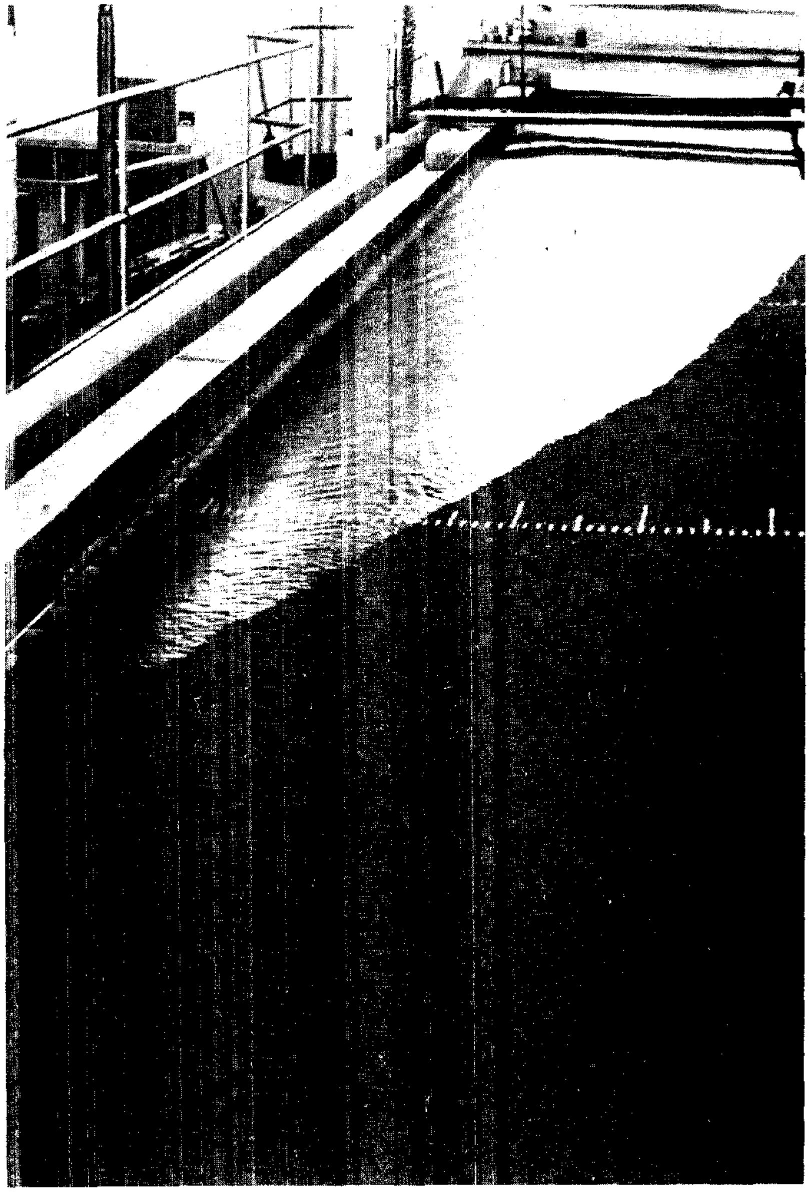


Figure 8. - A typical total flow capture test. Slot width = 1.75 in (44.45 mm), curb distance = 0, S_0 = 0.04, Z = 24, Q = 5.28 ft^3/s (0.150 m^3/s), Y = 0.251 ft (0.077 m), L = 35.6 ft (10.85 m), T = 6.50 ft (1.98 m).

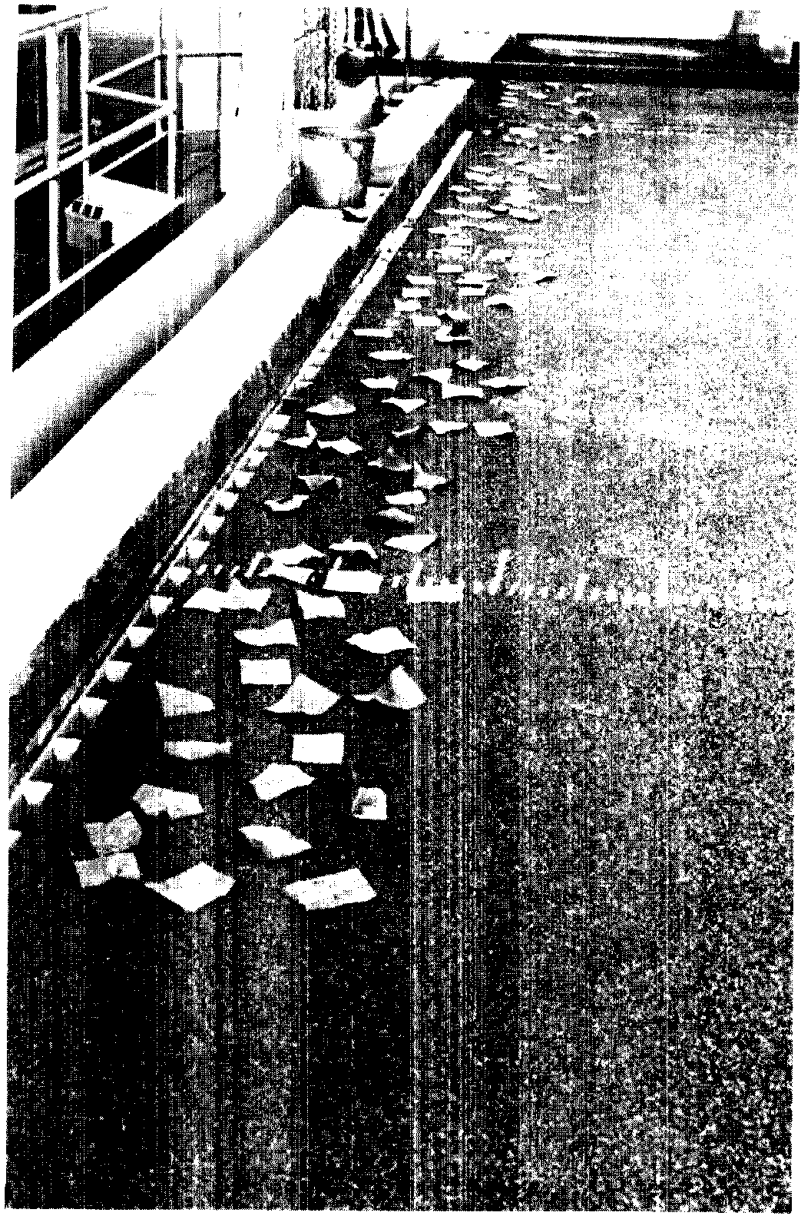


Figure 9. - Debris scattered on roadway prior to a debris test.

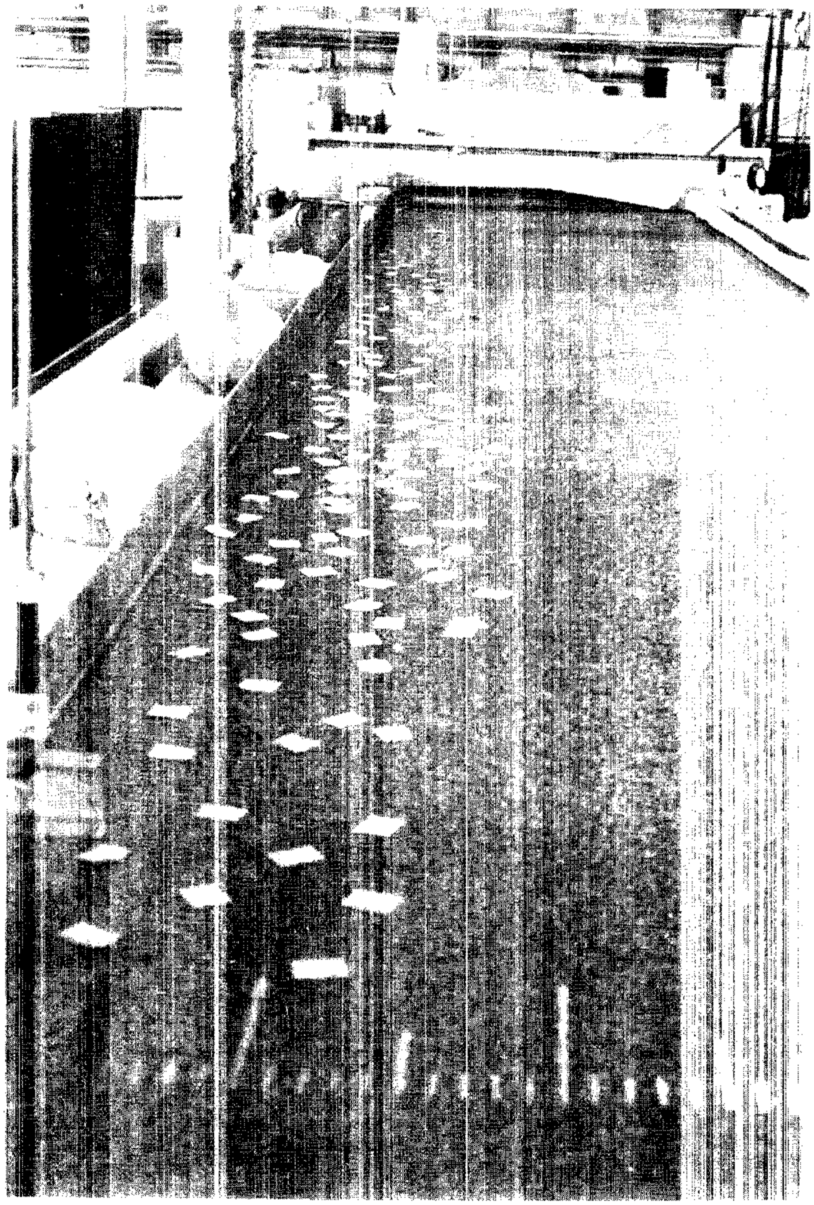


Figure 10. - Debris scattered on the roadway prior to a sump debris test.

CHAPTER 3

TOTAL FLOW INTERCEPTION TESTS

Introduction

Total flow interception tests were conducted to compare slotted drains in a variety of installations. In order to assess the effect of each parameter, individual parameters were changed while holding the others constant. The slope conditions tested for each parameter are listed in table 1. Parameters included in the testing were:

1. Roadway roughness
2. Transverse bar spacing and design
3. Slot width
4. Distance from curb and slot
5. Combined sheet flow and gutter flow

The following is an explanation of the legend in plots of 100 percent flow capture length:

Spacer - 45 at 6.00 - solid spacers at 45° angle, spaced at 6 in

DB at 6.00 - double bar spacers spaced at 6 in

SV at 6.00 - solid vertical spacers spaced at 6 in

SV SHEET-FL - solid vertical spacers spaced at 6 in with combined sheet flow and gutter flow

SM at 6.00 - solid vertical spacers spaced at 6 in, on smooth roadway surface: Manning's "n" = 0.009 (Smooth)

at 4.00 - spacers spaced at 4 in

S.W. - slot width - "inches"
Z - cross slope = 1/Z
So - longitudinal slope "ft/ft"
C.D. - curb distance "inches"

Roadway Roughness. - Tests were conducted on a slot with solid vertical transverse bars at 6-in (152.4-mm) spacing for two roadway roughnesses (SV-1.75-6-3.5). Figures 11 through 13 are test results for Manning's n = 0.009. Figures 14 through 16 are results for n = 0.0165. In figures 17, 18, and 19, some of the data are replotted to illustrate the effect of changing the Manning's n value while holding the other variables constant.

A comparison was made to study the effect of n on slot capacity at longitudinal slopes of 2, 4, and 6 percent, and gutter flows of 0.3, 0.8, and 2.0 ft^3/s (0.008, 0.023, and 0.057 m^3/s) at cross slopes of 1:24 and 1:48. Only data in the weir flow region were used for this comparison. The roughened surface resulted in an average reduction in required slot length of 18 percent. When weir flow is not controlling L the roughened surface reduces the required slot length by more than 18 percent.

Transverse Bar Spacing and Design. - The following types of transverse bars were tested for n = 0.165, curb distance = 3.50 in (88.9 mm), and slot width 1.75 in (44.45 mm). Figure 20 shows the test slots. The figures listed after the slot type give the test results.

1. Solid vertical bars at 6-in (152.4-mm) spacing (fig. 14 through 16)
2. Solid vertical bars at 4-in (101.6-mm) spacing (fig. 21 through 23)
3. Double hexagonal bars at 6-in (152.4-mm) spacing (fig. 24 through 26)
4. Double hexagonal bars at 4-in (101.1-mm) spacing (fig. 27 through 29)
5. Solid bars at 45° angle at 6-in (152.4-mm) spacing (fig. 30 through 32)

Figures 33 through 38 are comparisons of 100 percent capture lengths for the different transverse bar designs. The total flow capture efficiency of the different types of transverse bars is essentially the same for Z = 24 and 48. At Z = 16, the slot lengths are the same for discharges less than 2 ft^3/s (0.057 m^3/s). At higher discharges, the type of bar determines the efficiency. Double bars and 45° solid spacers have the same efficiency and follow the slope of weir equation (7/16 on a log-log plot of L vs. Q, see fig. 35) through the entire range of data tested. Solid transverse bars block the flow and cause more overflow. Consequently, L is more for solid transverse bars in the high flow, steep slope range (fig. 34).

Slot Width. - Slot widths of 1.00 in (25.4 mm), 1.75 in (44.45 mm), and 2.50 in (63.5 mm) were tested for solid vertical spacers at 6 in (152.4 mm) at n = 0.0165, with a 3.50-in (88.9-mm) curb distance. Figure 39 shows the three slots tested.

Figures 40 through 42 present test results for the 1-in (25.4-mm) wide slot. Figures 14 through 16 present test results for the 1.75-in (44.45-mm) wide slot and results for the 2.50-in (63.50-mm) wide slot are presented in figures 43 through 45. Figures 46 through 51 are log-log plots, comparing results using different slot widths.

At Z = 48, the slot length (L) is essentially the same for all three slot widths (fig. 48). The variation at the high longitudinal slopes is probably due to inaccuracy in determining the capture lengths at these slope conditions (fig. 51). The flow is very shallow and the velocity is high at flat cross slopes and steep longitudinal slopes, making it very difficult to determine L.

At Z = 24, the 1.75-in (44.45-mm) wide and 2.50-in (63.5-mm) wide slots have about the same efficiency. The 1-in (25.4-mm) wide slot has about the same efficiency as the wider slots up to about 2.5 ft^3/s (0.071 m^3/s), where the efficiency decreases (fig. 50).

At Z = 16, the 1.00-in (25.4-in) wide slot is again less efficient than the wider slots at high discharges. The 1.75-in (44.45-mm) wide slot is less efficient than the 2.50-in (63.5-mm) wide slot at longitudinal slopes S_o above 2 percent at flows above 3.5 ft^3/s (0.099 m^3/s) (fig. 49).

Curb Distance. - Tests were conducted on an SV-1.75-6 slot at curb distances of 0, 3.50, and 7.00 in (0, 88.9, and 177.8 mm). Figures 52 through 54 are plots for curb distance = 0. Figures 14 through 16 are results for C.D. = 3.50, and figures 55 through 56 are for C.D. = 7.00. Figures 57 through 59 compare results for the three curb distances. The effect of a variable curb distance on L was small at Z = 48. The difference in L in figure 59 is due to difficulty in determining length for this combination of slope conditions.

At Z = 16, the installations with the larger curb distance are slightly more efficient at low discharges. This is because the width of spread on the roadway side of the slot is less for larger curb distances since more of the flow is contained on the curb side of the slot. At higher discharges, the large curb distances are less efficient (fig. 59). This is because there is more area for the excess flow to accumulate on the curb side of the slot and move longitudinally down the roadway. The installation with the curb adjacent to the slot is the most efficient at high discharges because the curb face tends to guide the flow into the slot and the flow contraction is reduced.

Combined Sheet Flow and Gutter Flow. - A series of tests was performed to determine if combining sheet flow with gutter flow has any effect on the 100 percent capture length. In these tests, a constant sheet flow of q = 0.025 ft^3/s per ft (0.22 L/s per m) was added to the gutter flow (fig. 60). In actual field conditions, flow would build up gradually along the roadway upstream from the slot and part of the flow would come across the road directly into the slot. The length along the roadway where sheet flow was introduced depended on the amount of gutter flow. Care was taken not to overflow the 100 percent capture point for gutter flow only by introducing too much sheet flow. Figures 61 through 63 present results of the total capture tests for combined sheet and gutter flow. Figures 64 through 67 compare slot lengths for combined flow to slot lengths for gutter flow only. These plots show that the addition of sheet flow has little effect on the 100 percent capture length. The combined flow data are essentially the same as the gutter flow data. Therefore, the data in figures 61 through 63 can be used to supplement the data for an SV-1.75-6-3.5 slot installation (fig. 14 through 16).

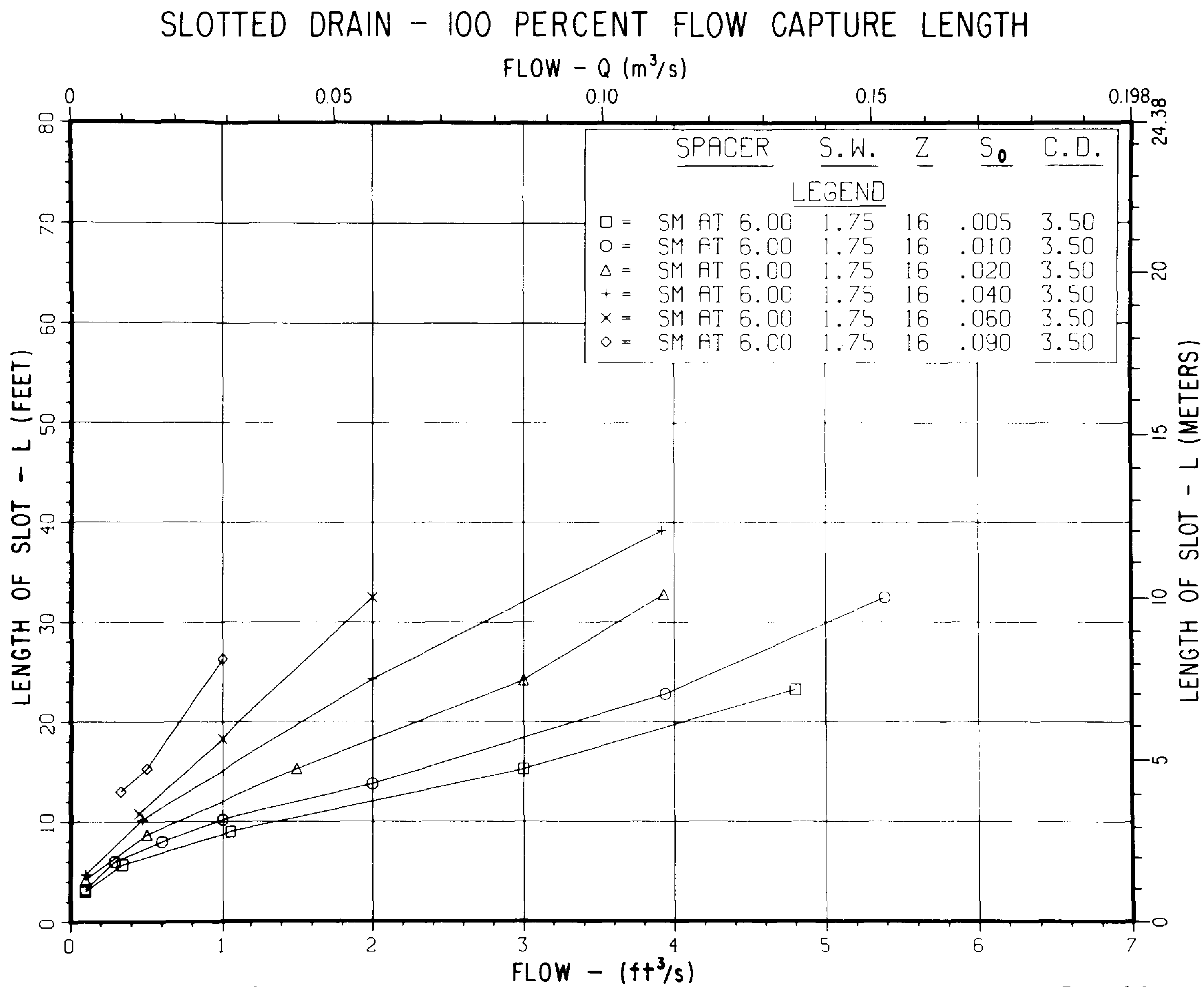


Figure 11. - 100 percent flow capture length for SM-1.75-6-3.5 at Z = 16.

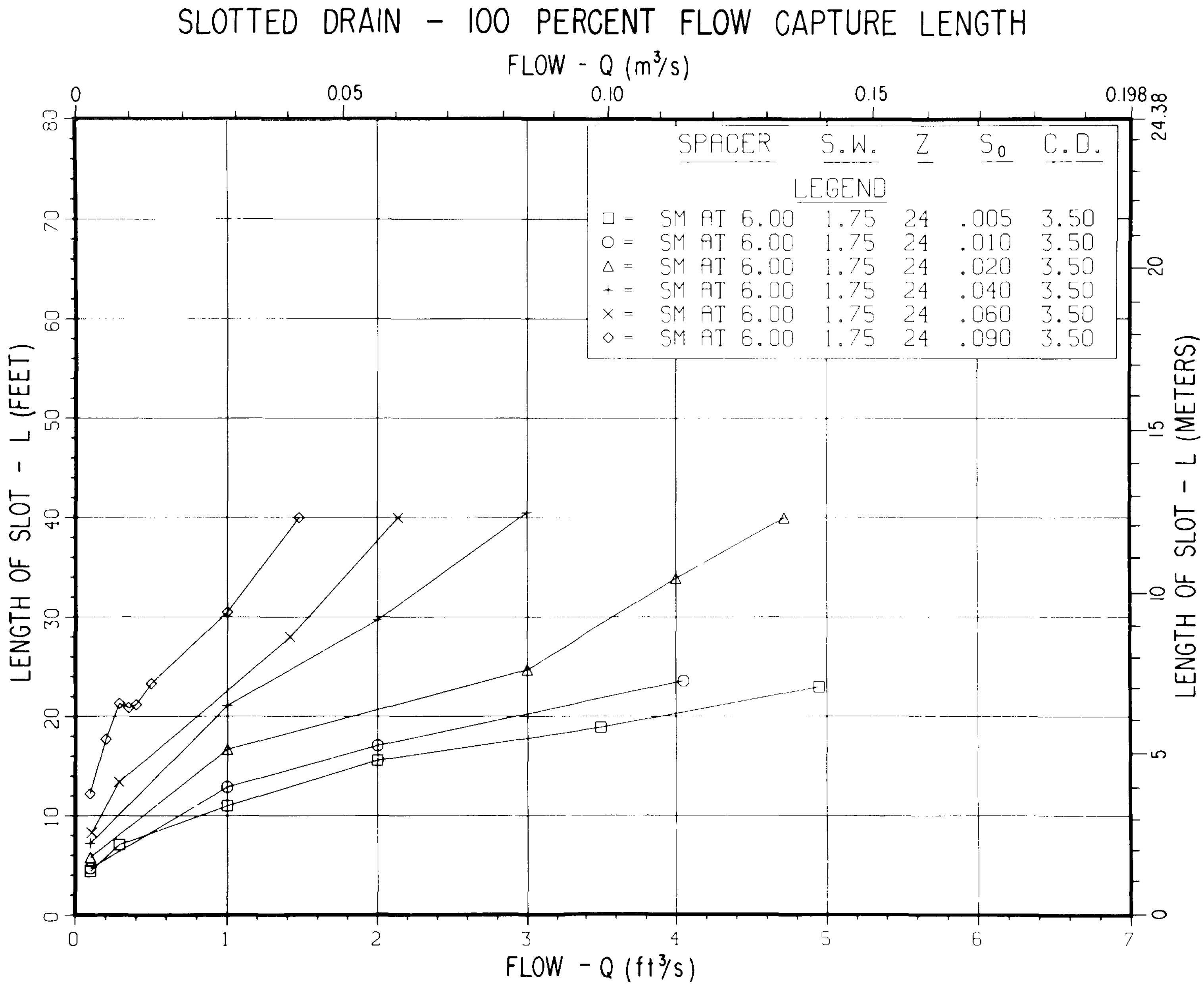


Figure 12. - 100 percent flow capture length for SM-1.75-6-3.5 at Z = 24.

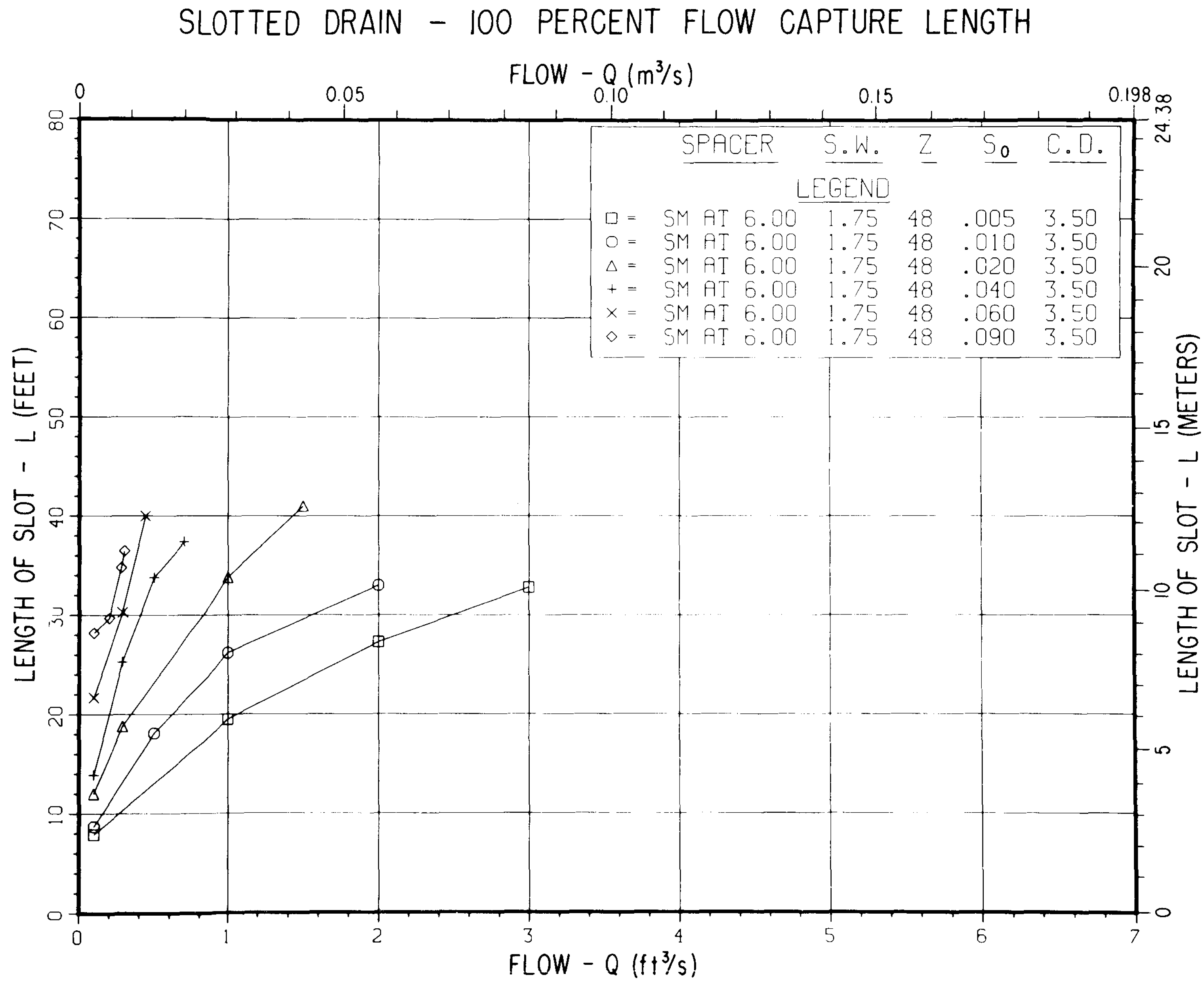


Figure 13. - 100 percent flow capture length for SM-1.75-6-3.5 at Z = 48.

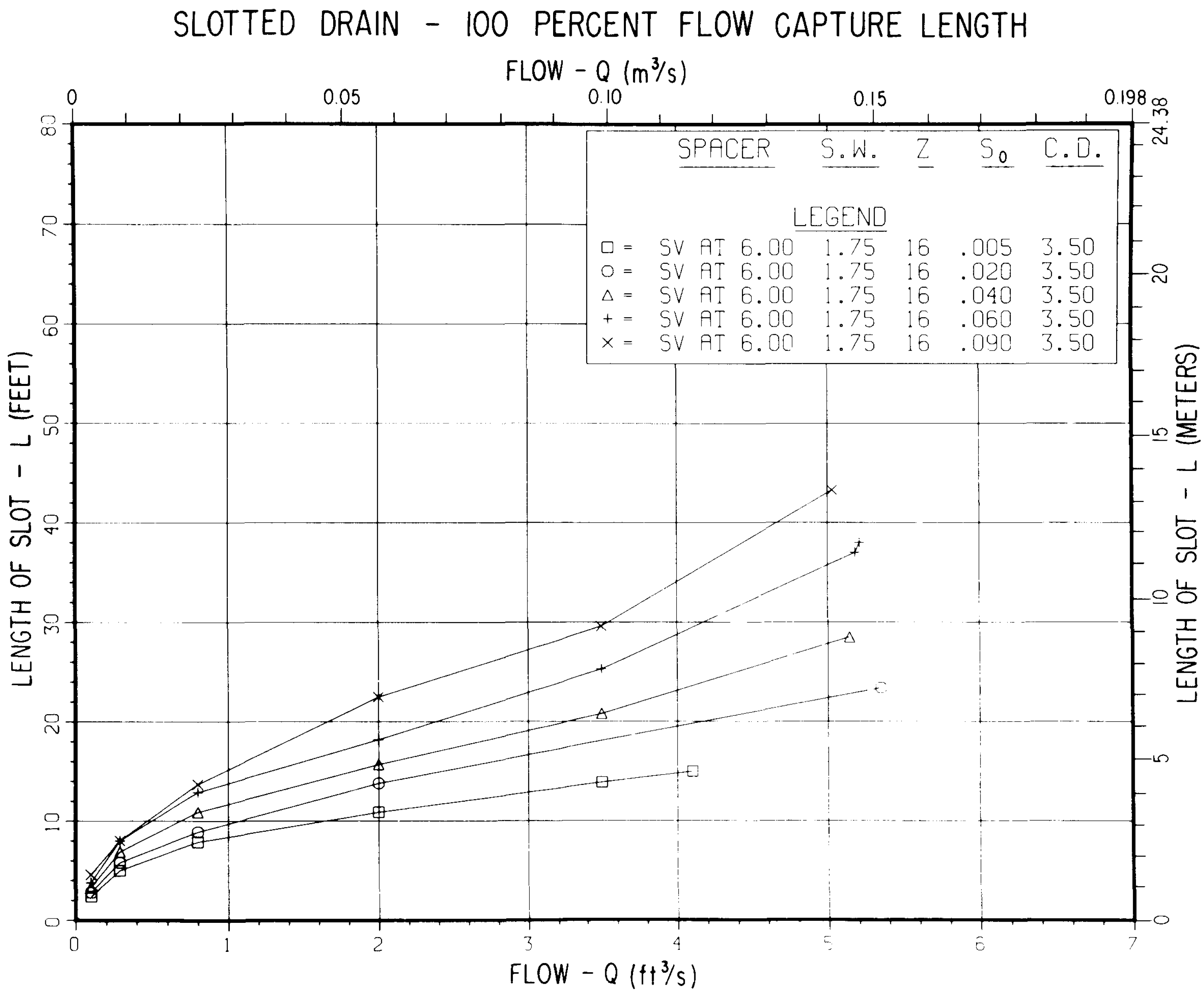


Figure 14. - 100 percent flow capture length for SV-1.75-6-3.5 at Z = 16.

SLOTTED DRAIN - 100 PERCENT FLOW CAPTURE LENGTH

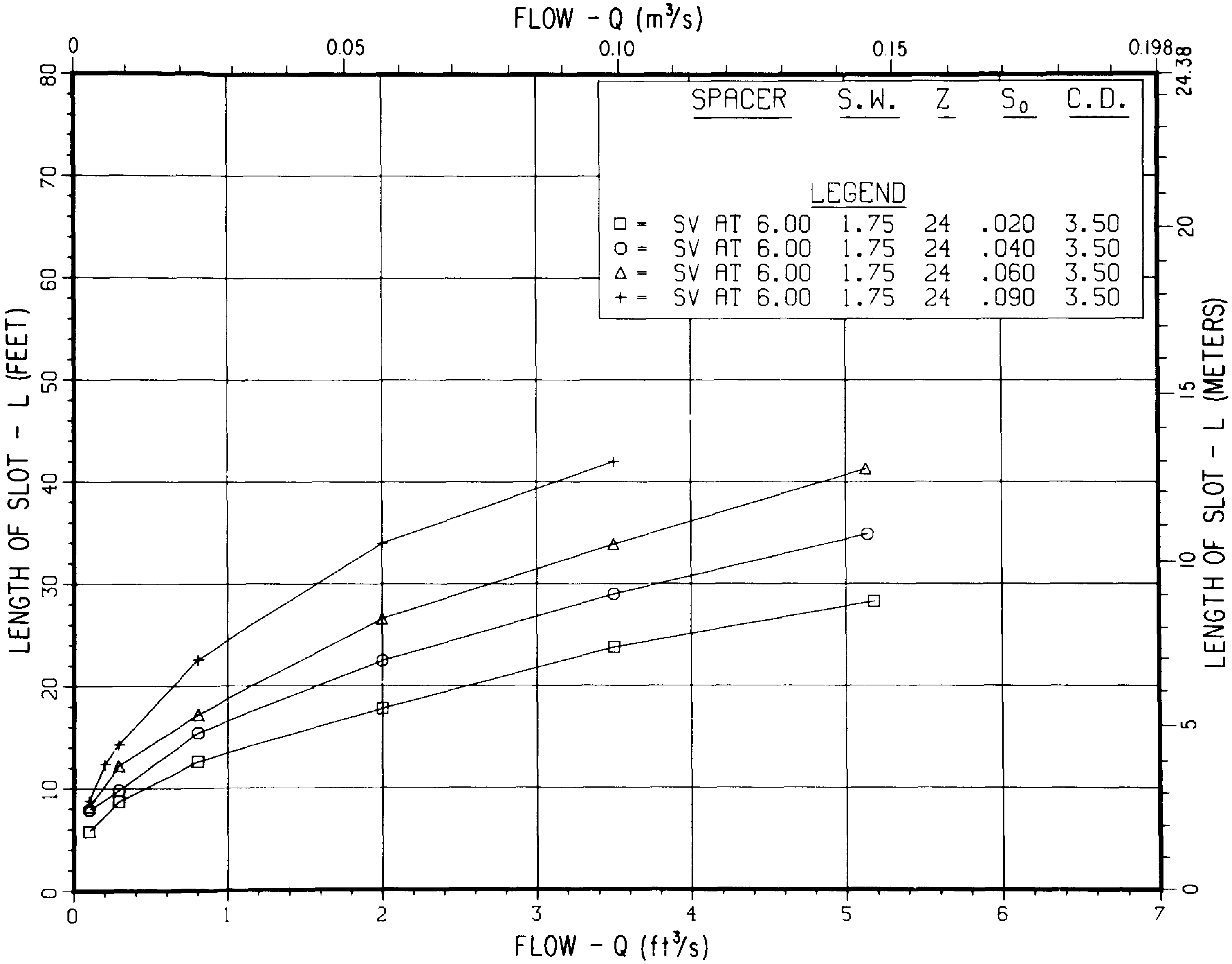


Figure 15. - 100 percent flow capture length for SV-1.75-6-3.5 at Z = 24.

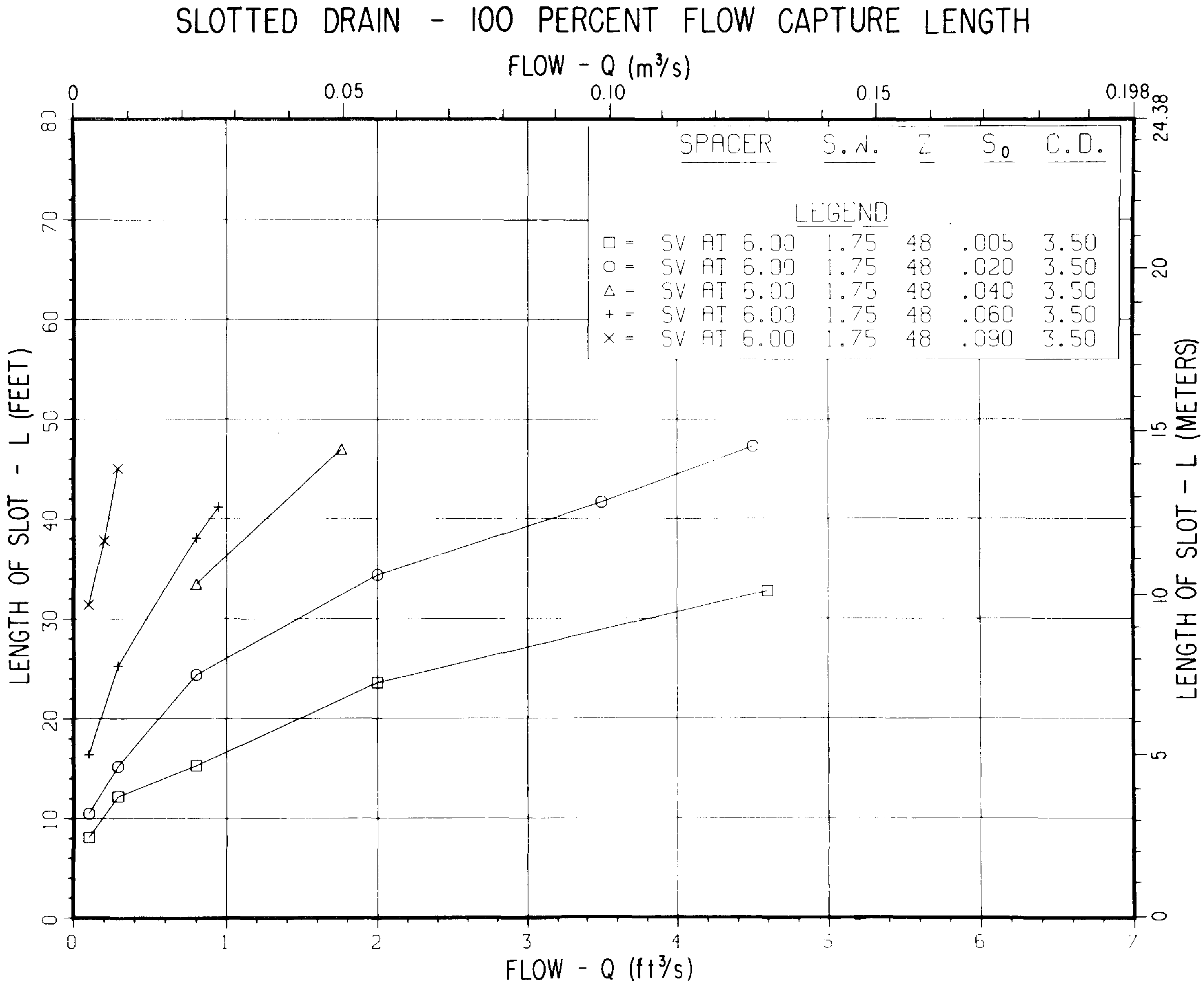


Figure 16. - 100 percent flow capture length for SV-1.75-6-3.5 at Z = 48.

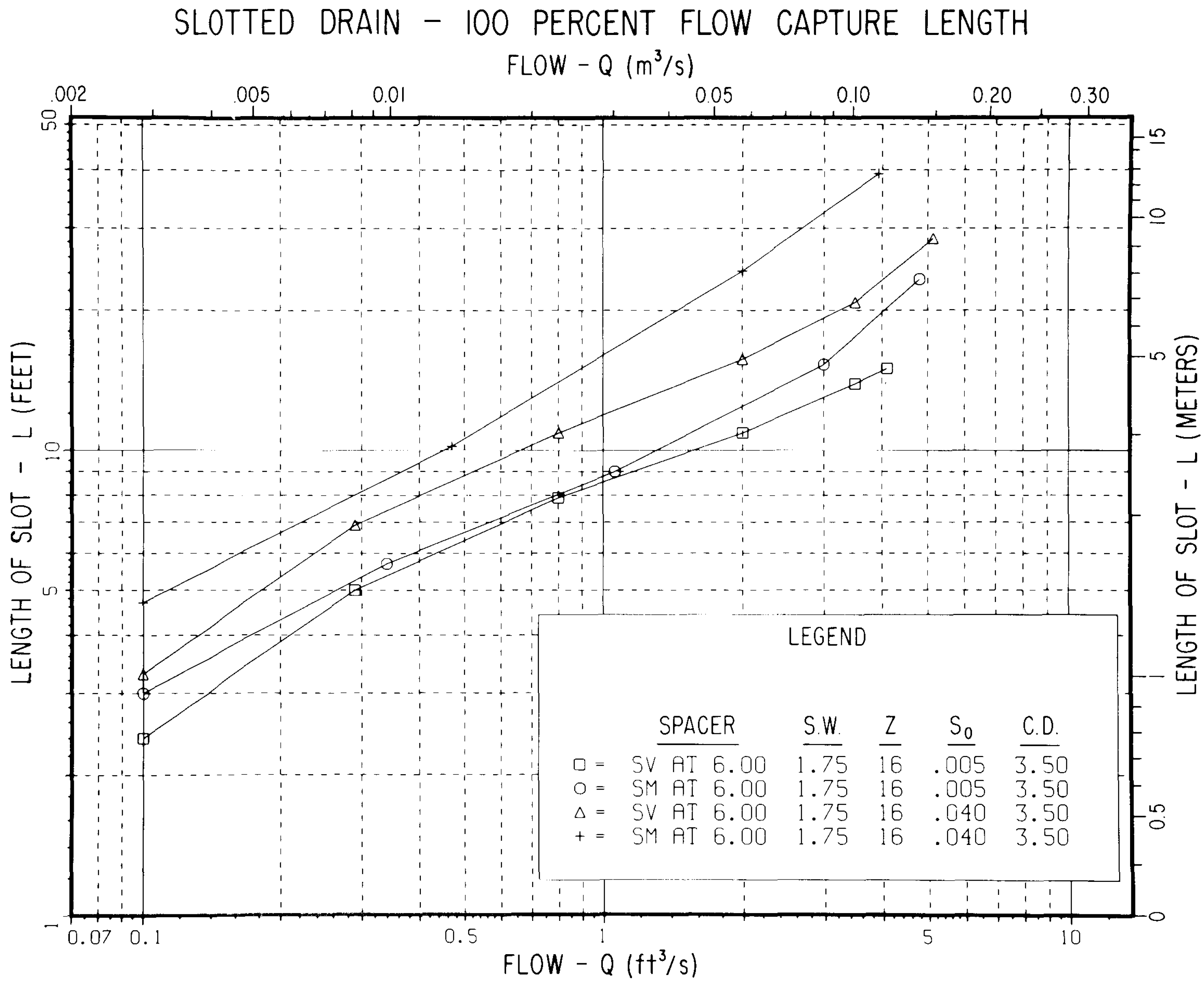


Figure 17. - Surface roughness effect (log-log) SV at 6.00 vs. SM at 6.00 (n = 0.0165 vs. 0.009) Z = 16; So = 0.005, 0.04.

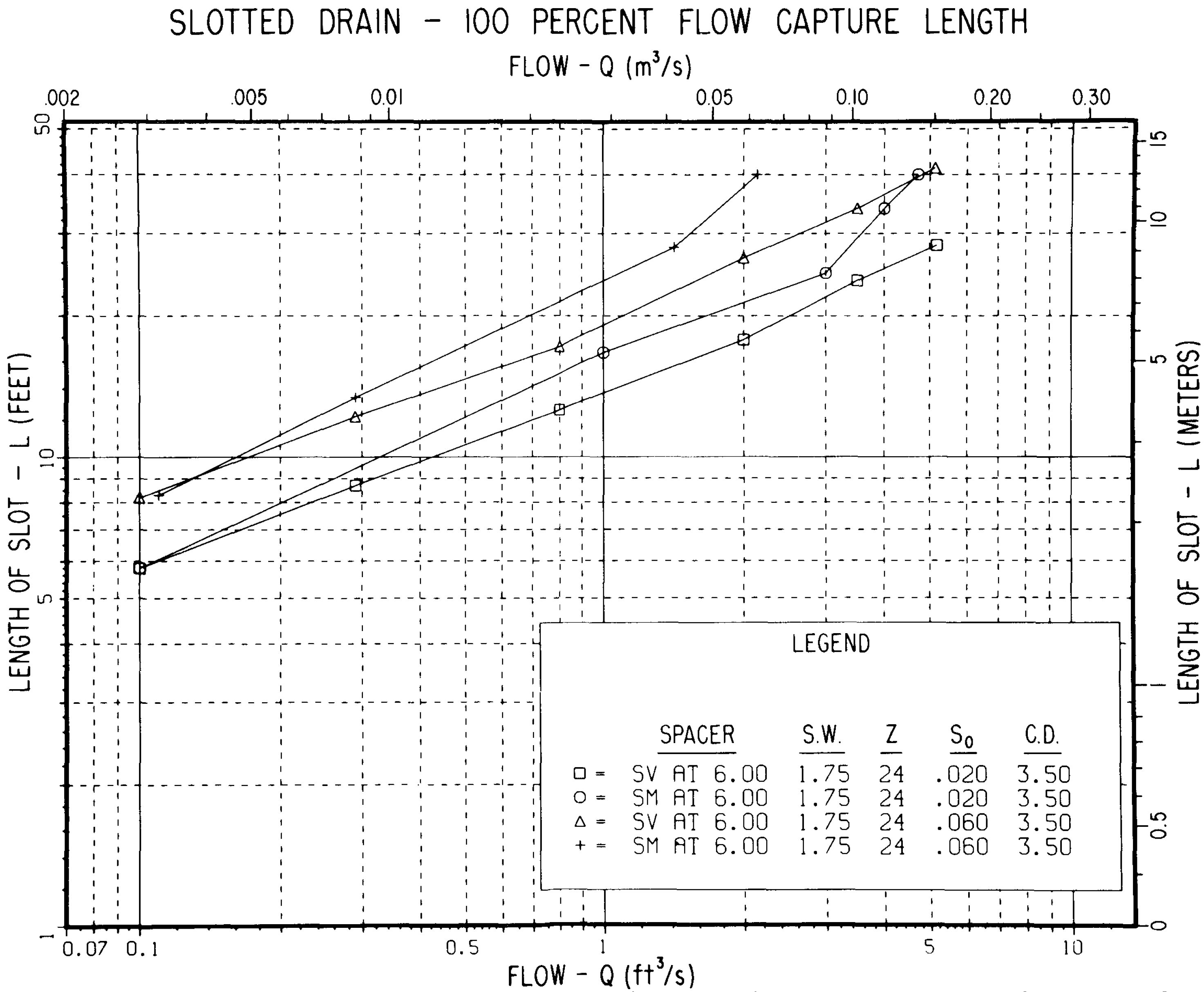


Figure 18. - Surface roughness effect (log-log) SV at 6.00 vs. SM at 6.00 (n = 0.0165 vs. 0.009) Z = 24; So = 0.02, 0.06.

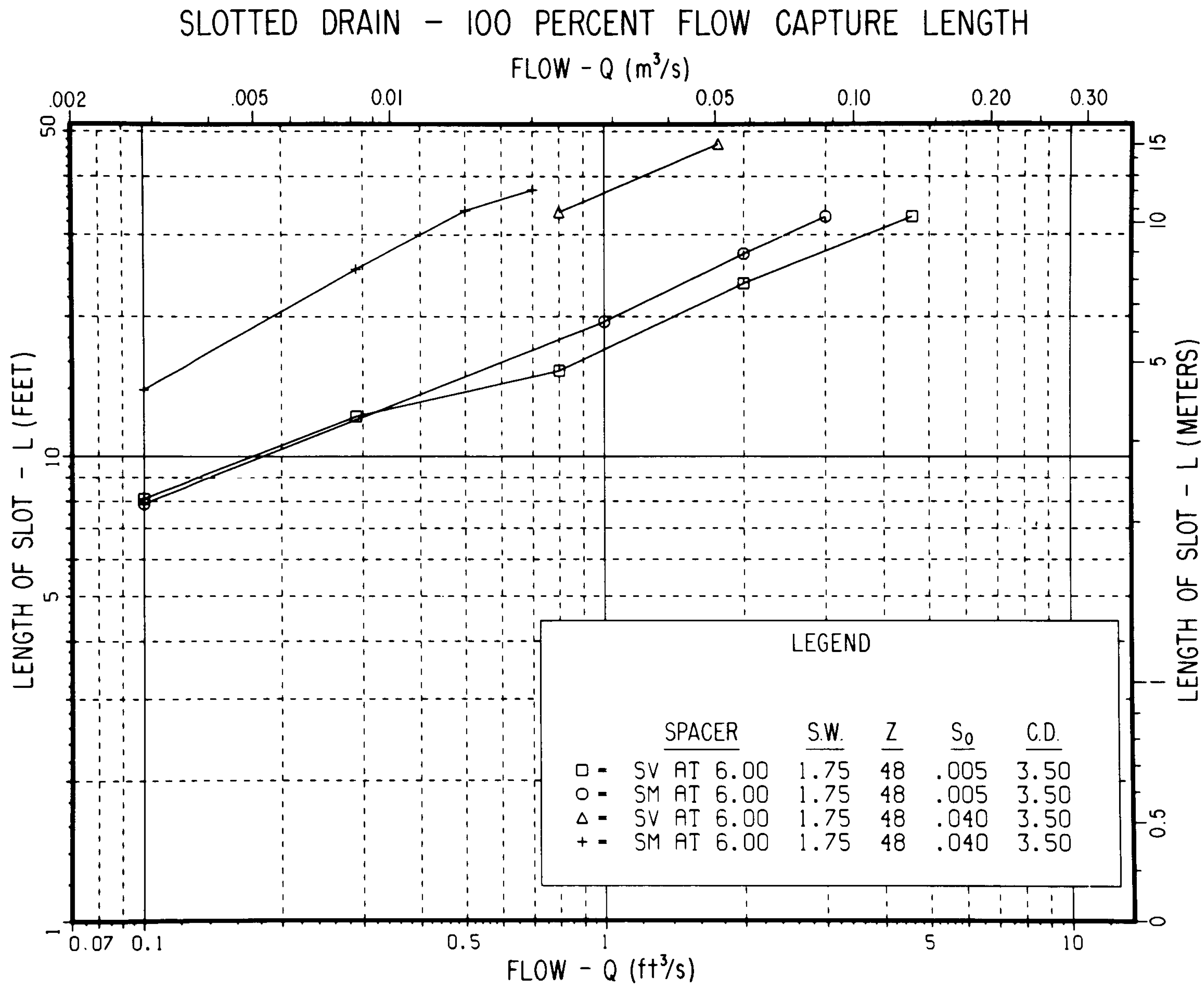
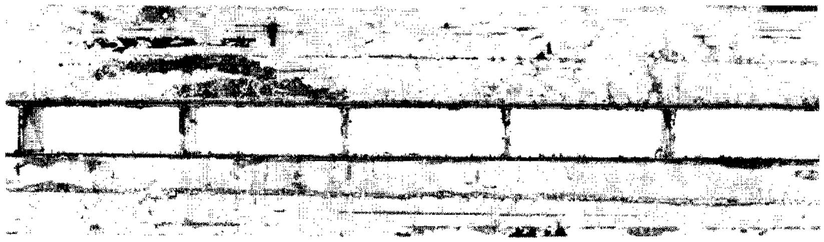
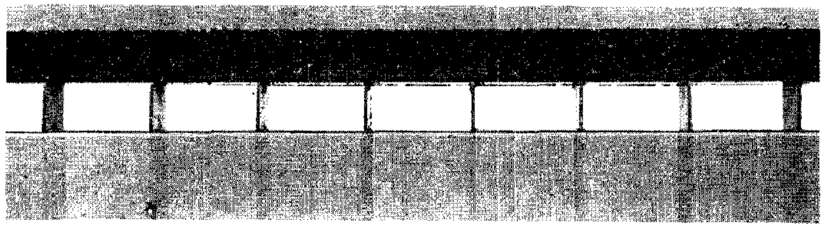


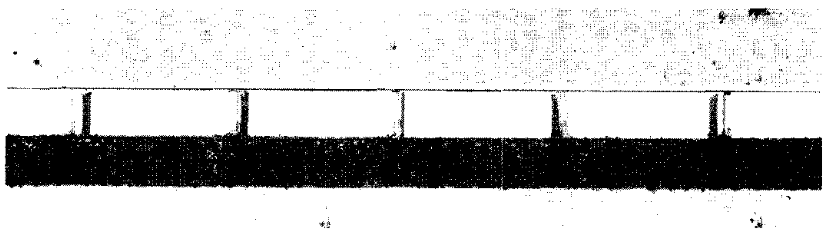
Figure 19. - Surface roughness effect (log-log) SV at 6.00 vs. SM at 6.00 (n = 0.0165 vs. 0.009) Z = 48; So = 0.005, 0.04.



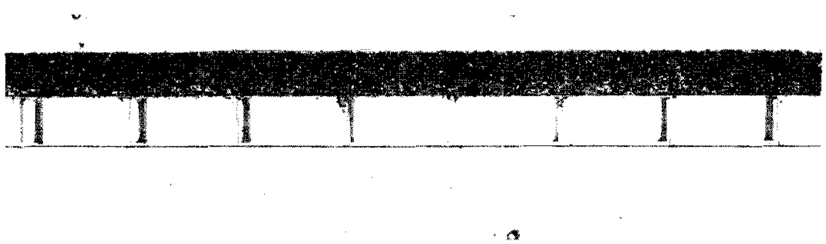
a. SV-1.75-6.



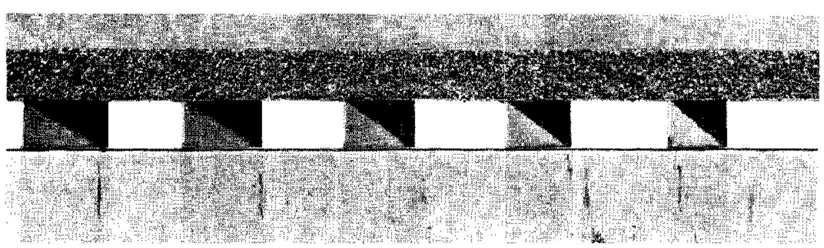
b. SV-1.75-4.



c. DB-1.75-6.



d. DB-1.75-4.



e. 45-1.75-6.

Figure 20. - Test slots with different types of transverse spacers (top view).

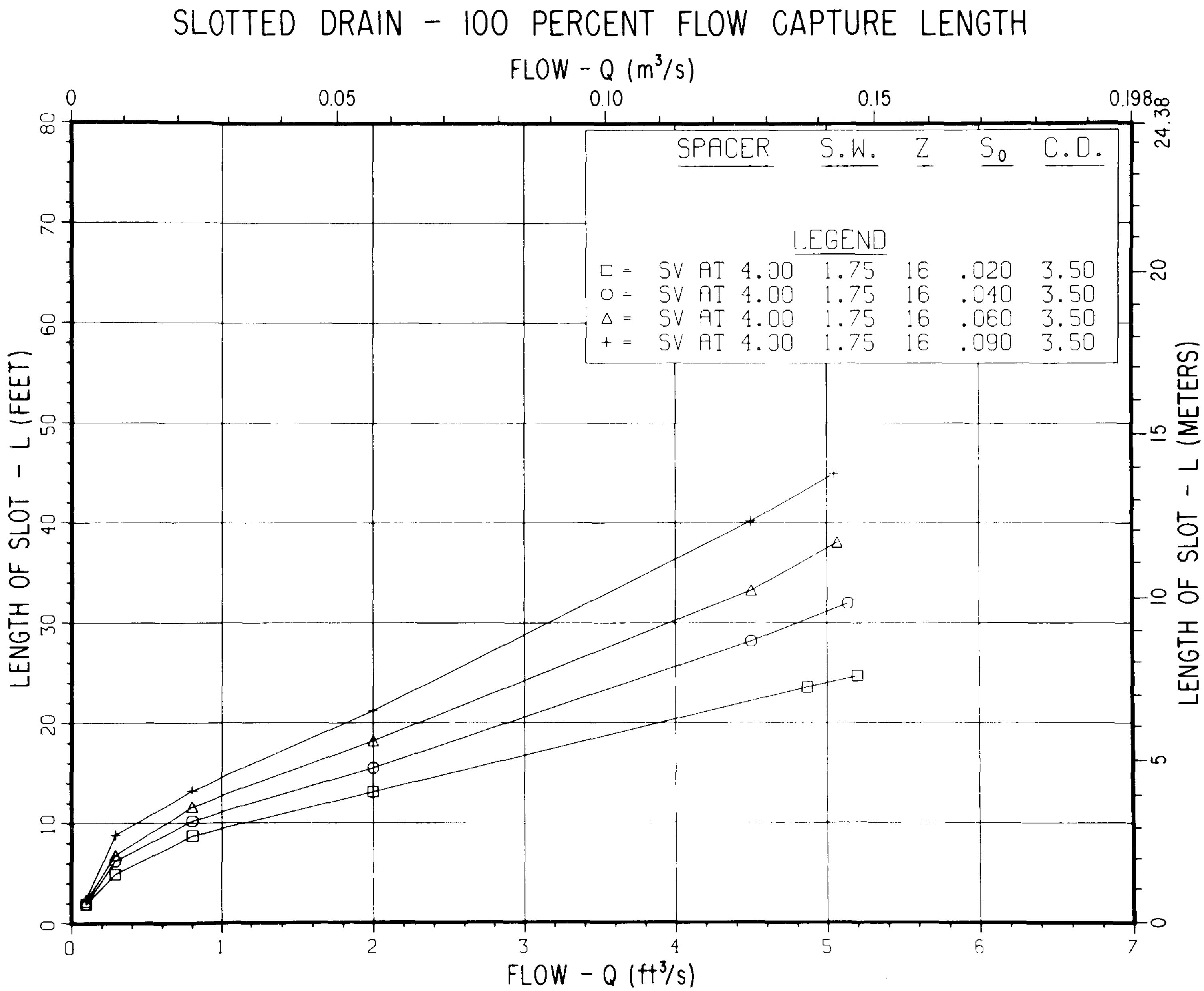


Figure 21. - 100 percent flow capture length for SV-1.75-4-3.5 at Z = 16.

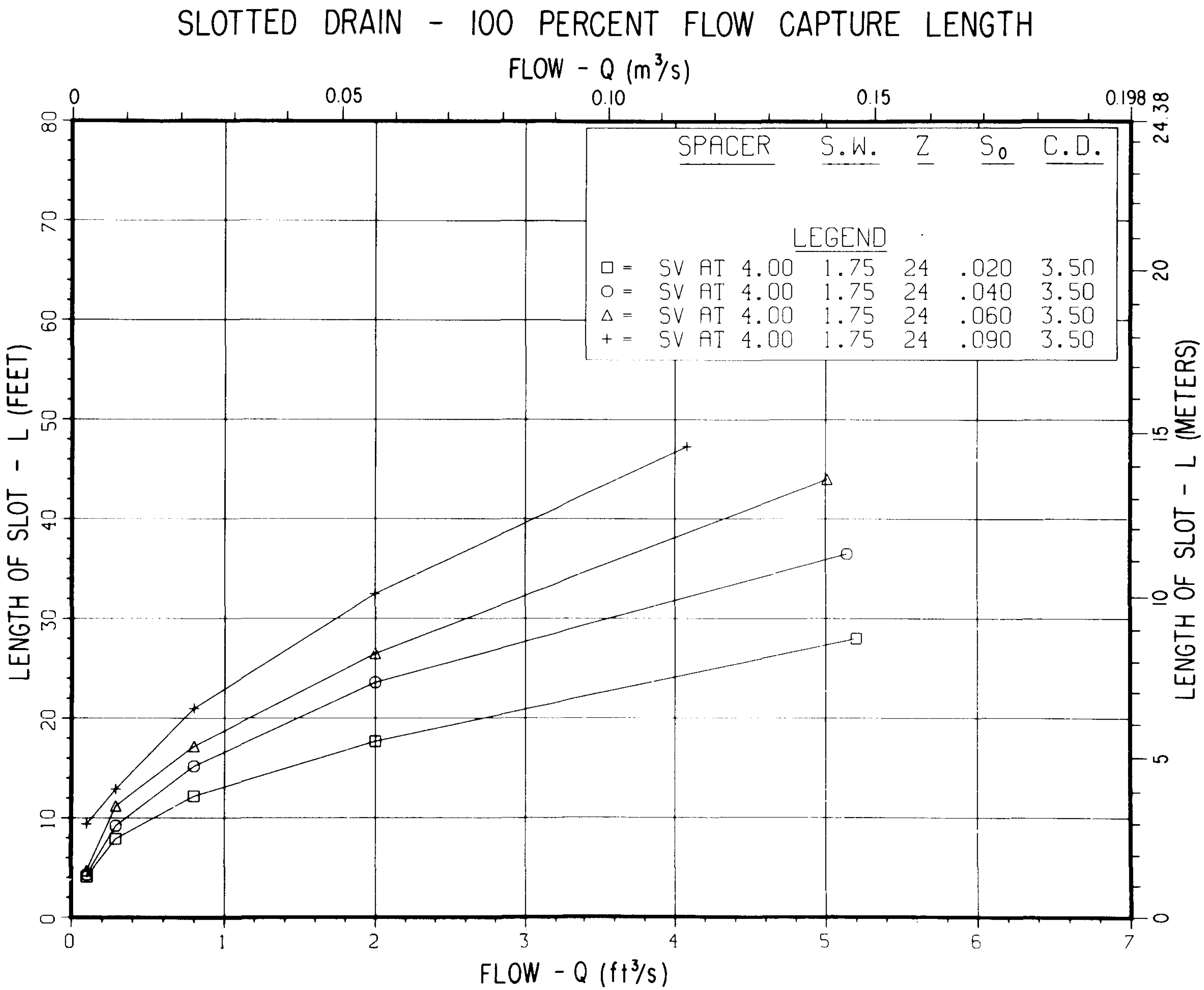


Figure 22. - 100 percent flow capture length for SV-1.75-4-3.5 at Z = 24.

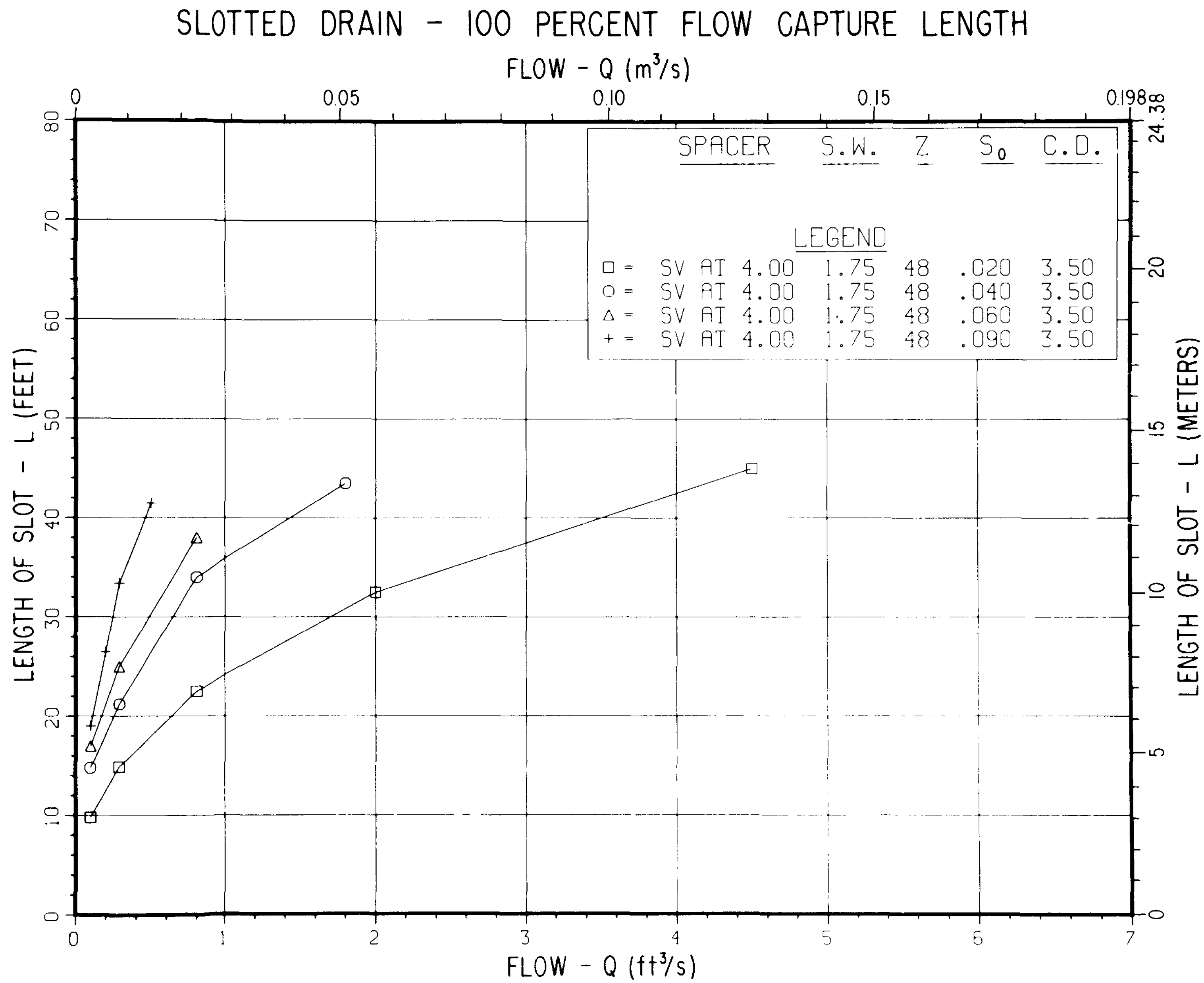


Figure 23. - 100 percent flow capture length for SV-1.75-4-3.5 at Z = 48.

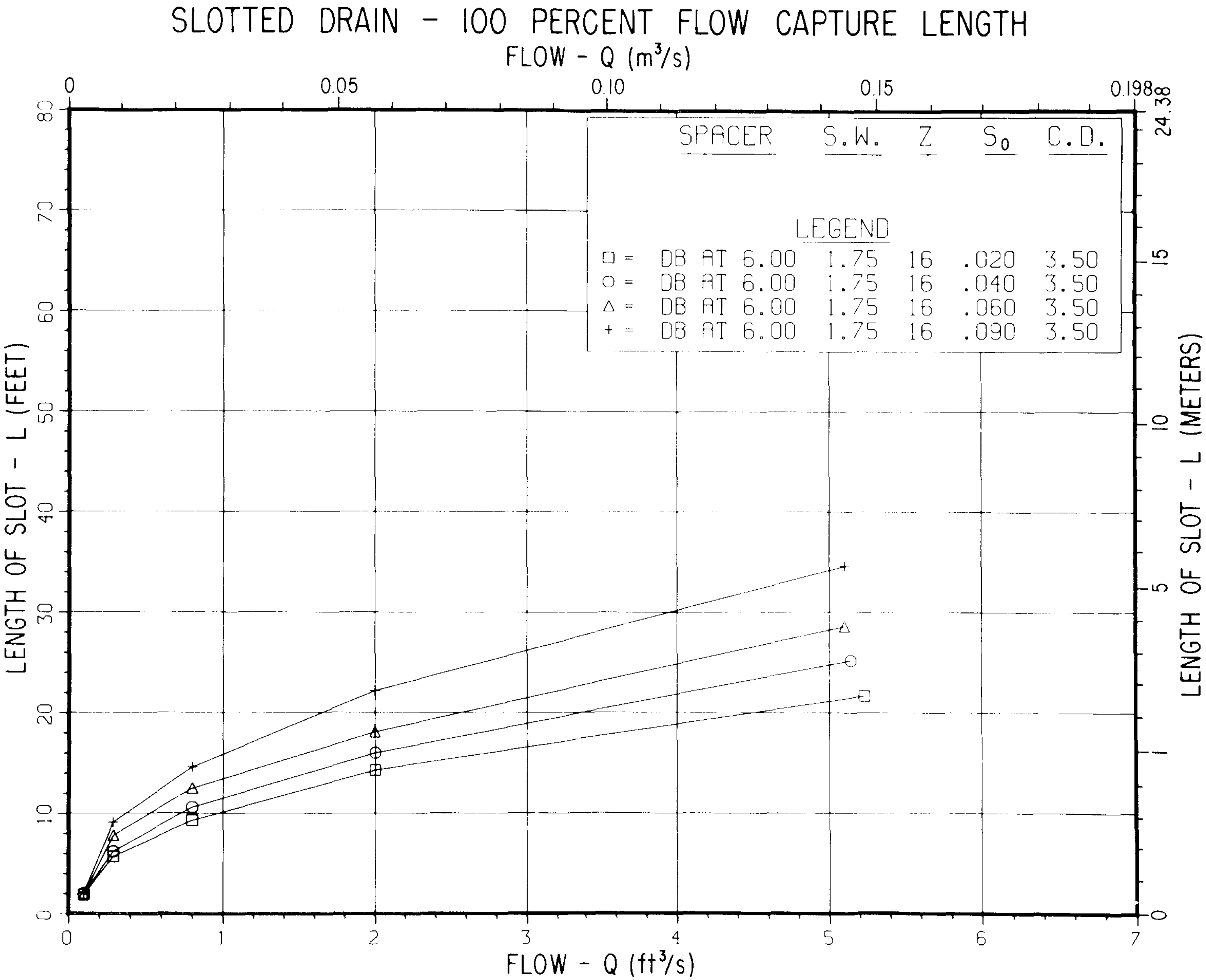


Figure 24. - 100 percent flow capture length for DB-1.75-6-3.5 at Z = 16.

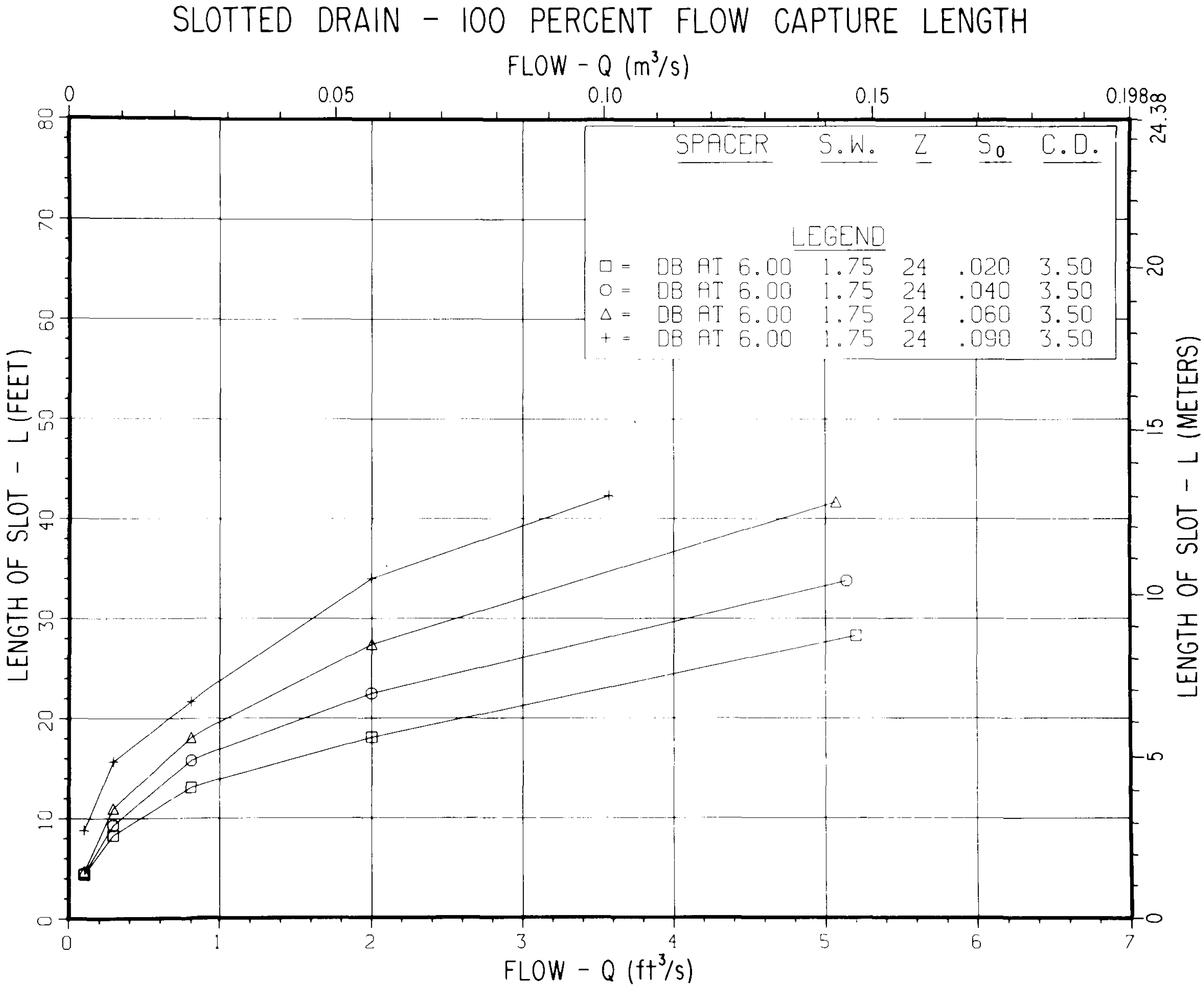


Figure 25. - 100 percent flow capture length for DB-1.75-6-3.5 at Z = 24.

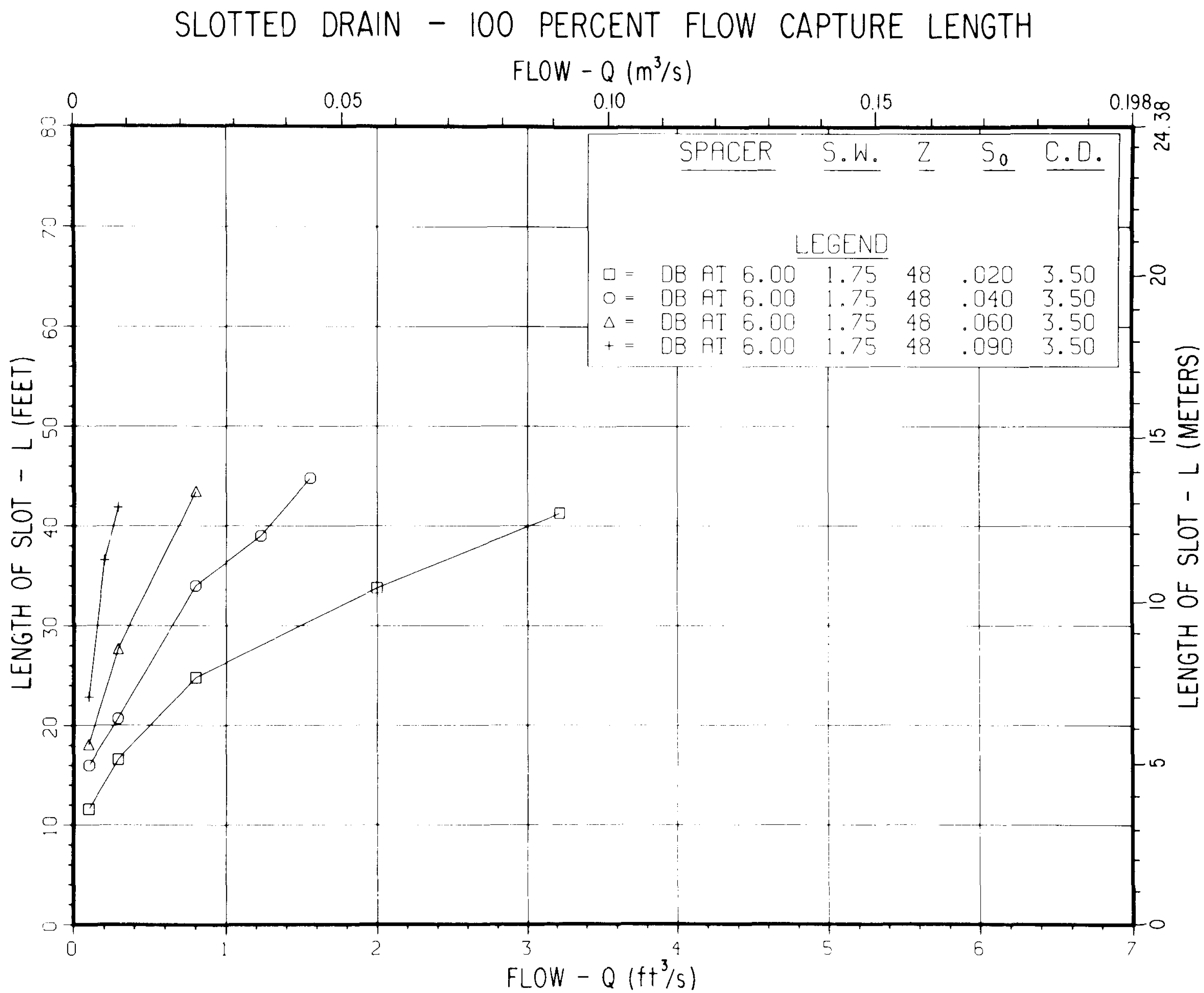


Figure 26. - 100 percent flow capture length for DB-1.75-6-3.5 at Z = 48.

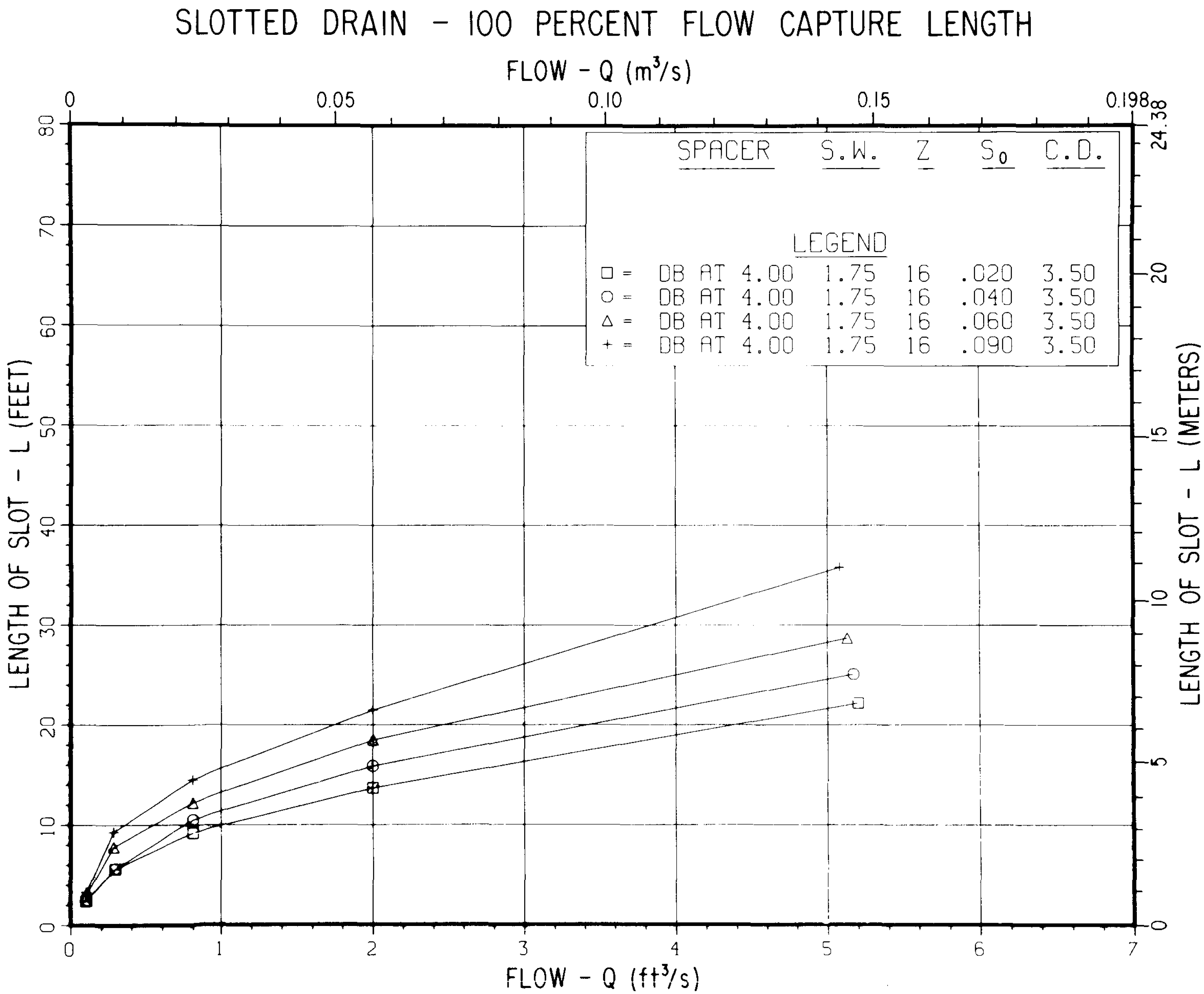


Figure 27. - 100 percent flow capture length for DB-1.75-4-3.5 at Z = 16.

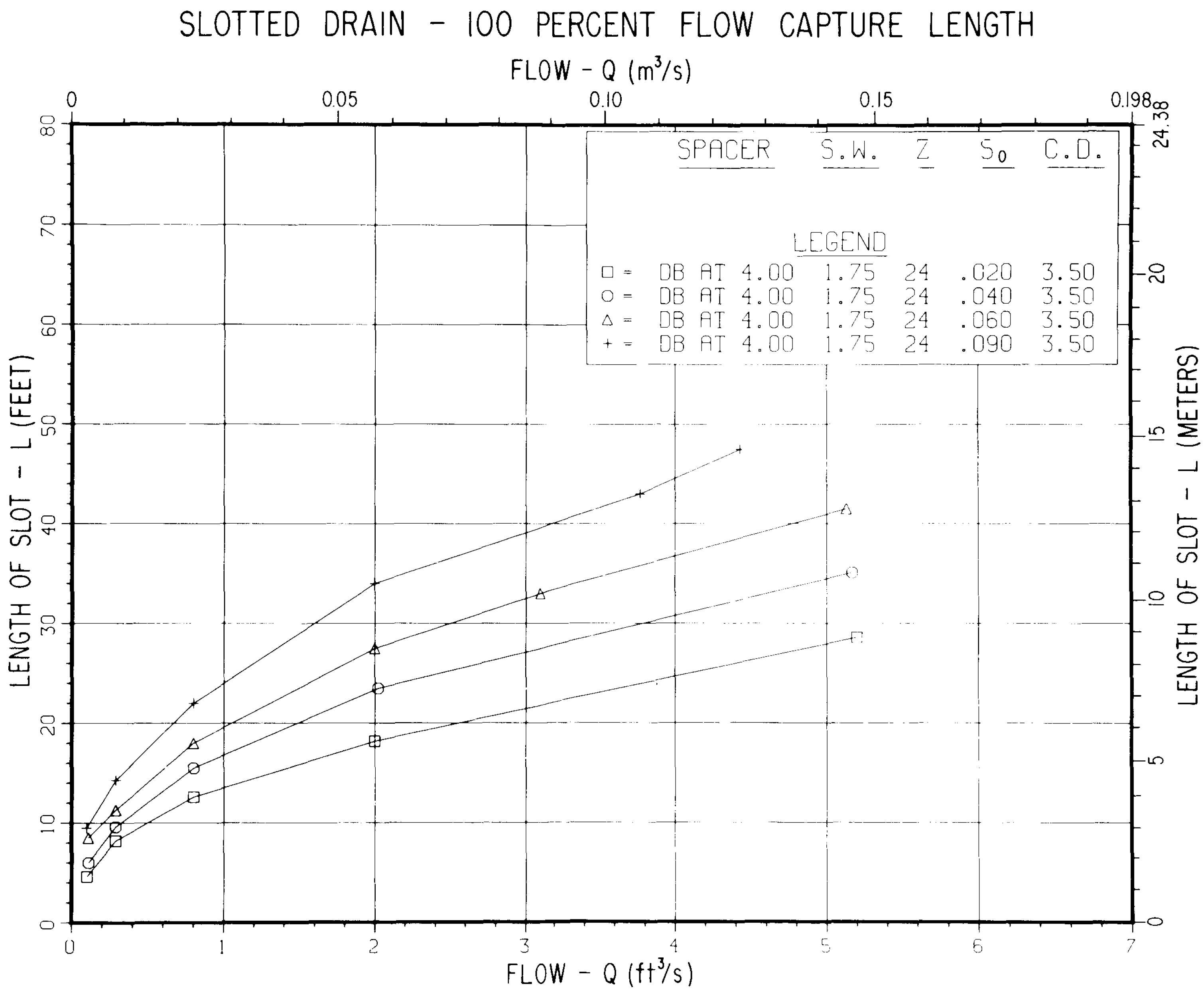


Figure 28. - 100 percent flow capture length for DB-1.75-4-3.5 at Z = 24.

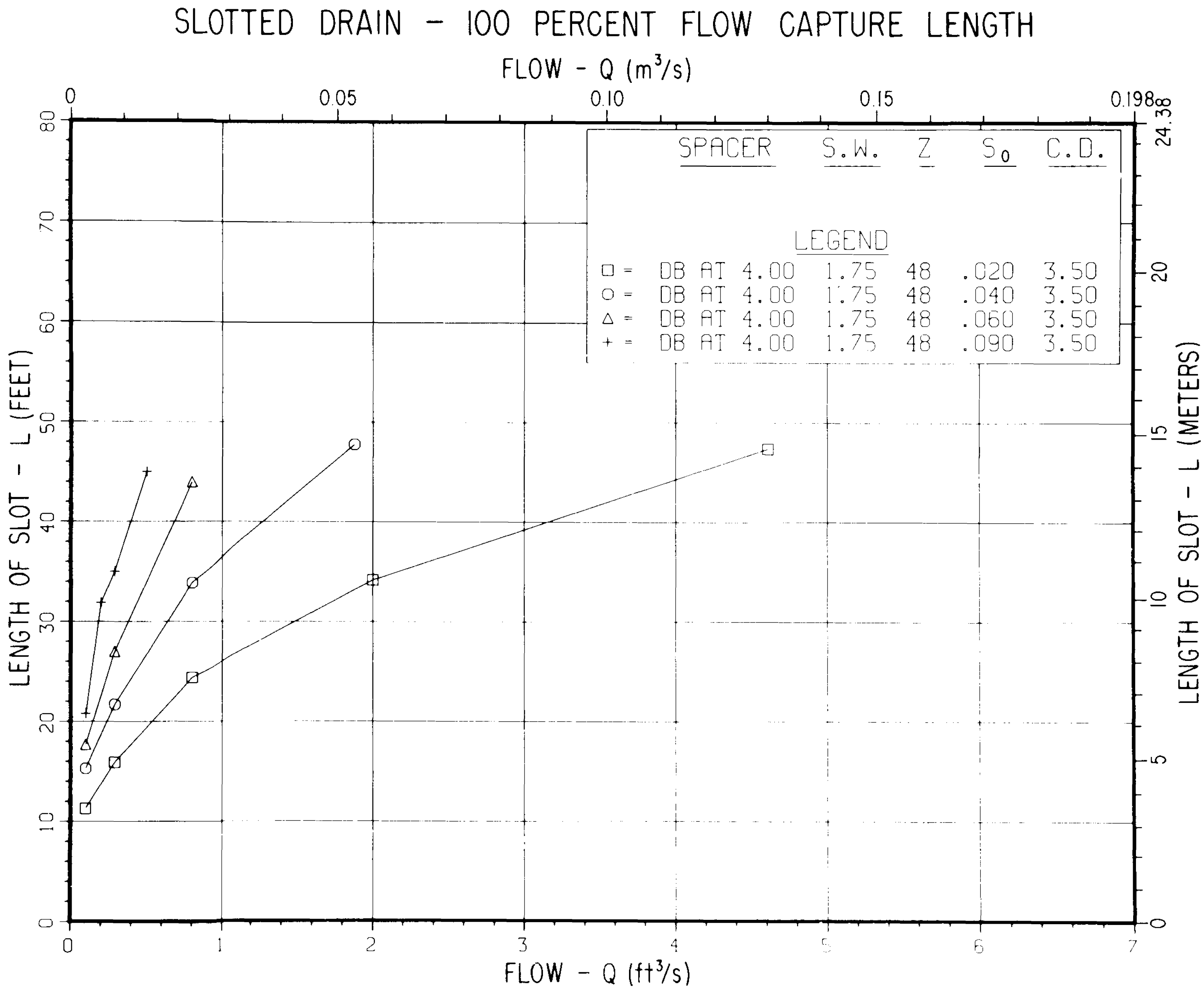


Figure 29. - 100 percent flow capture length for DB-1.75-4-3.5 at Z = 48.

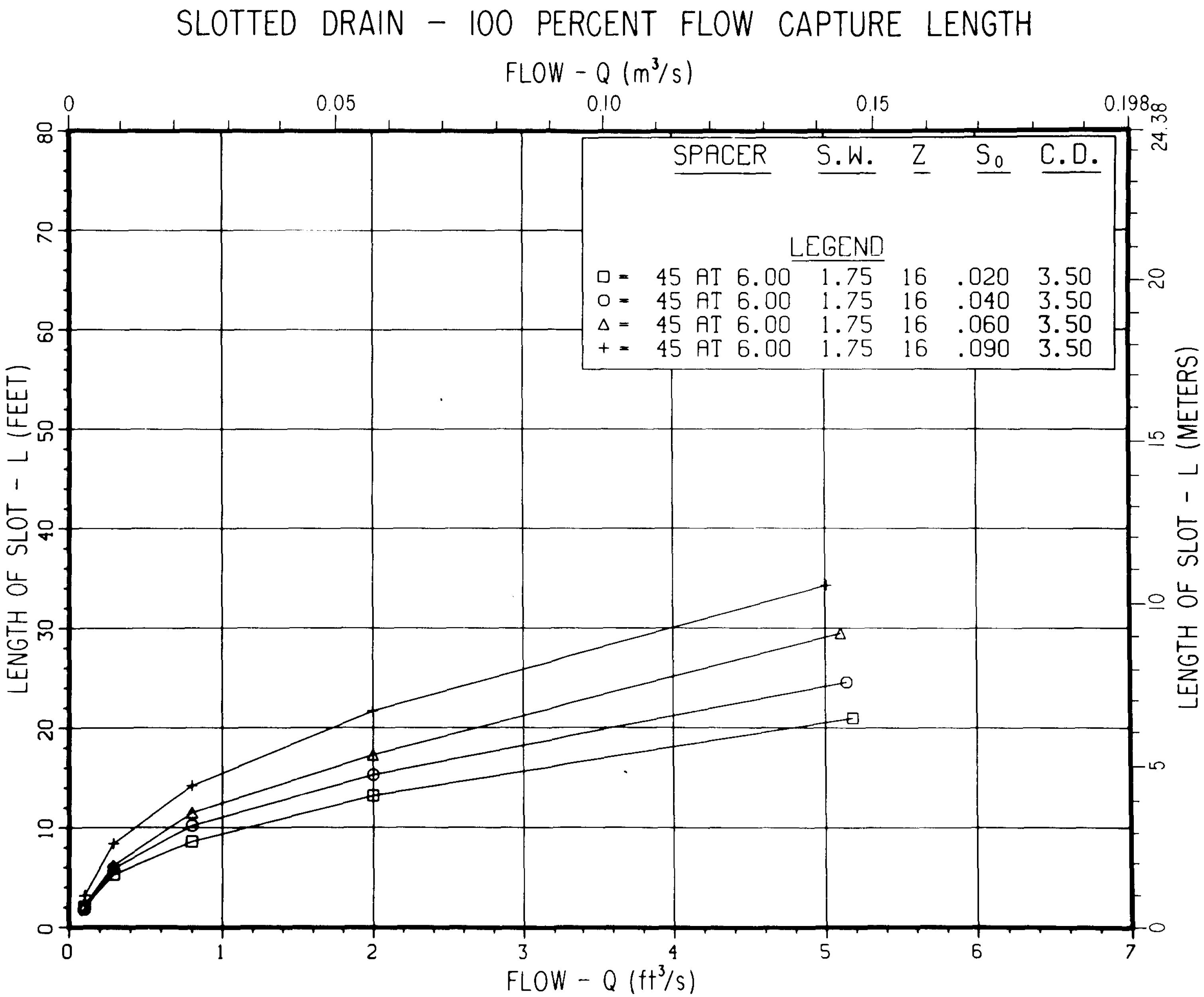


Figure 30. - 100 percent flow capture length for 45-1.75-6-3.5 at Z = 16.

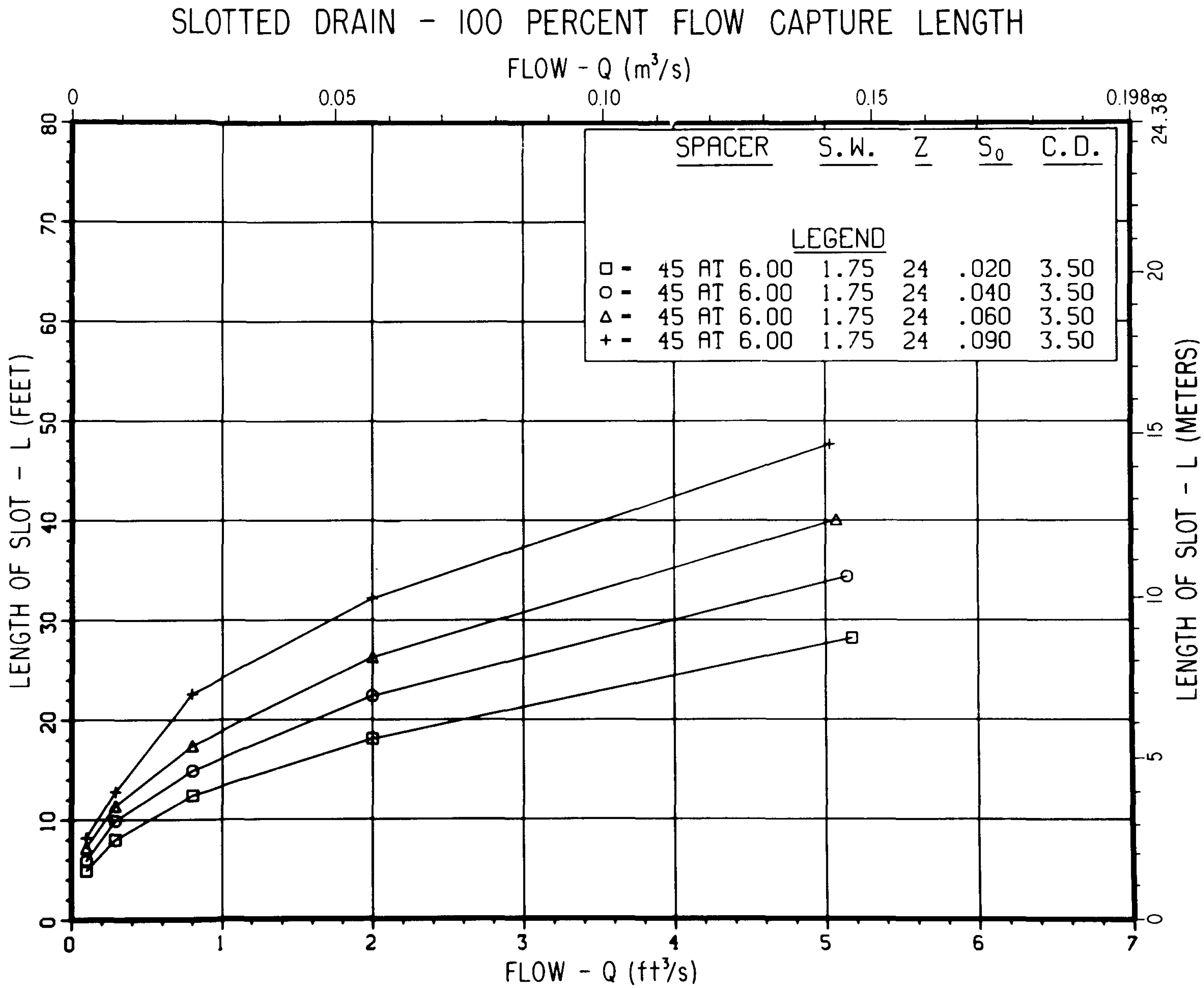


Figure 31. - 100 percent flow capture length for 45-1.75-6-3.5 at Z = 24.

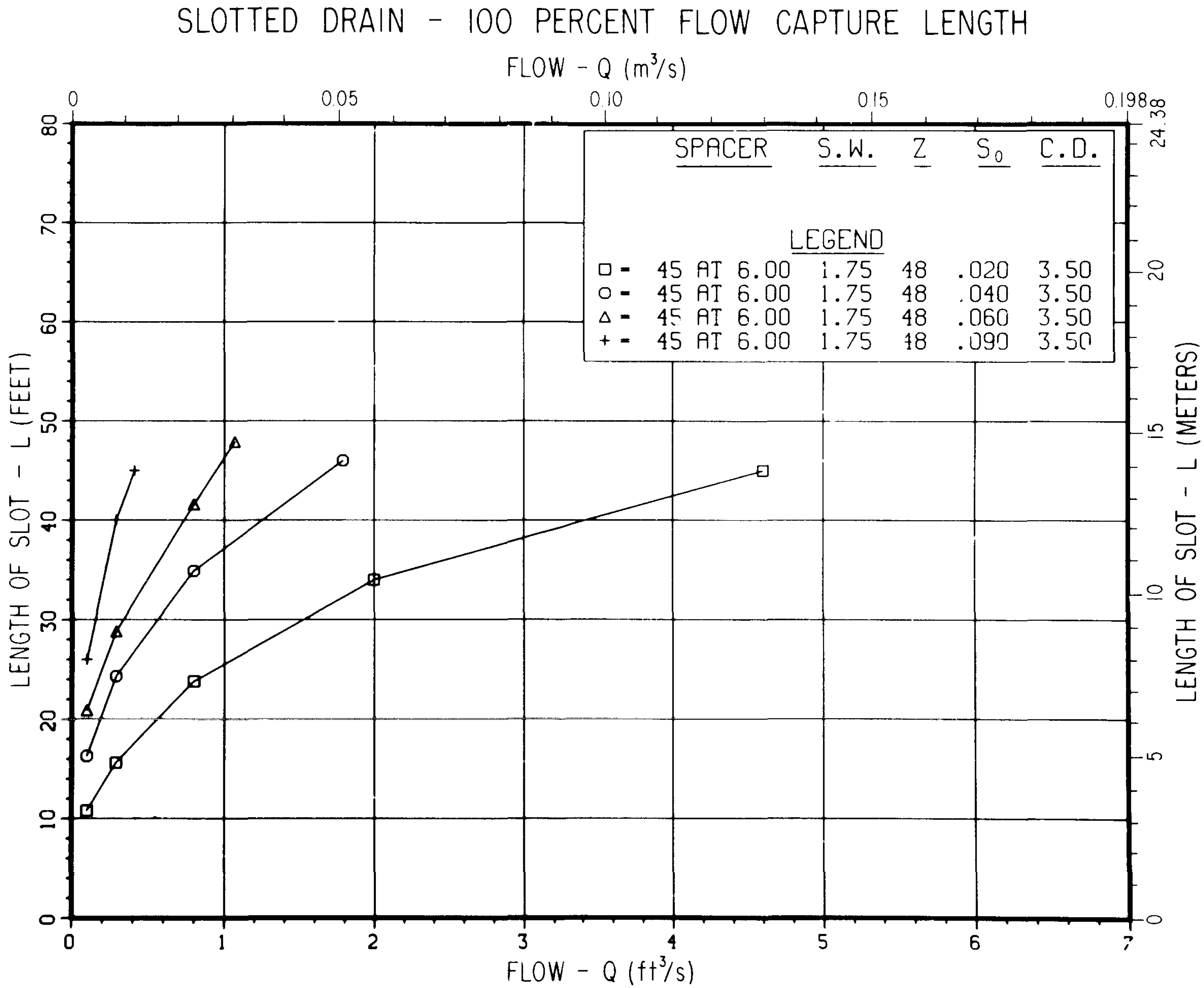


Figure 32. - 100 percent flow capture length for 45-1.75-6-3.5 at Z = 48.

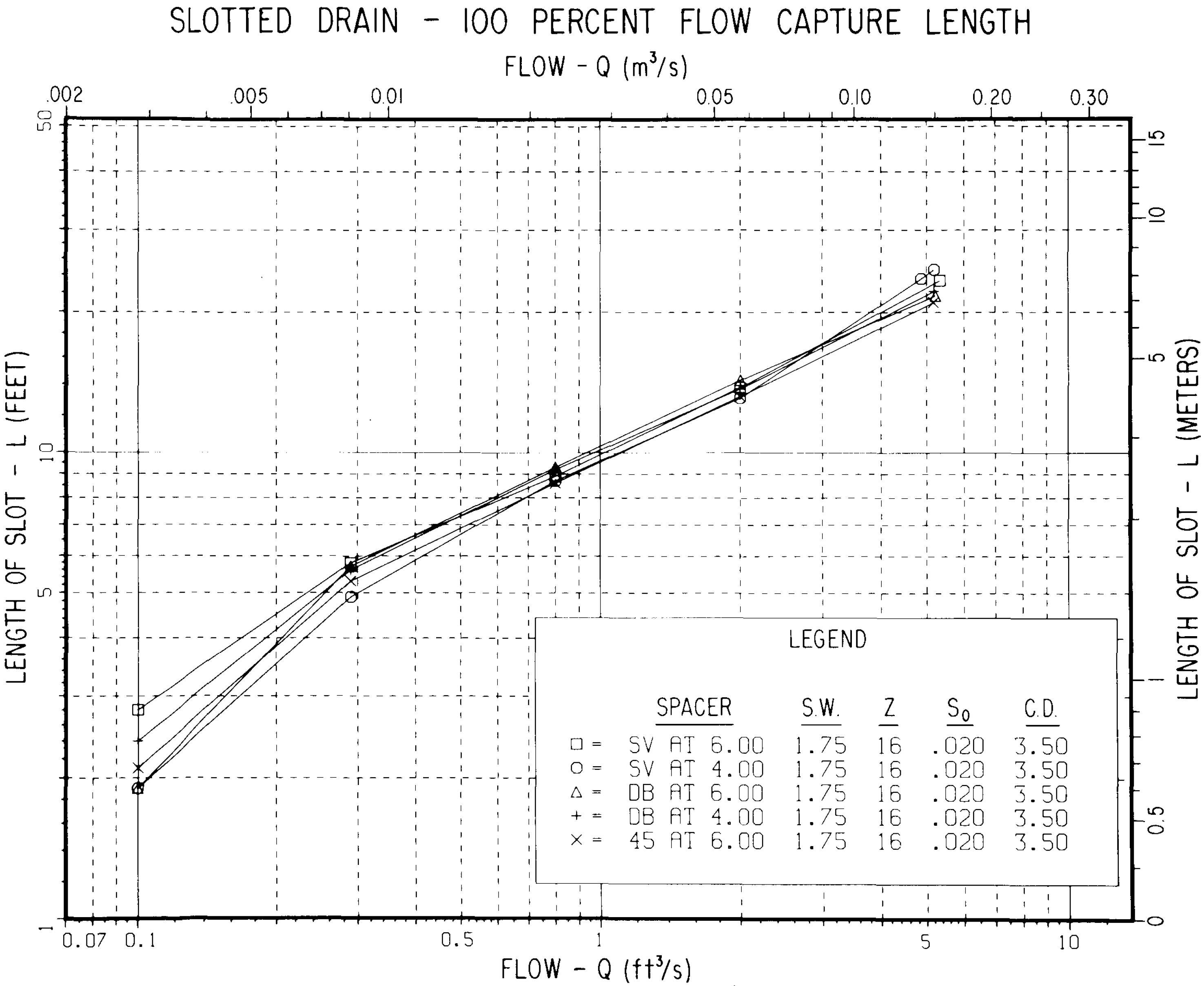


Figure 33. - Spacer type and spacing effect (log-log) Z = 16, So = 0.02.

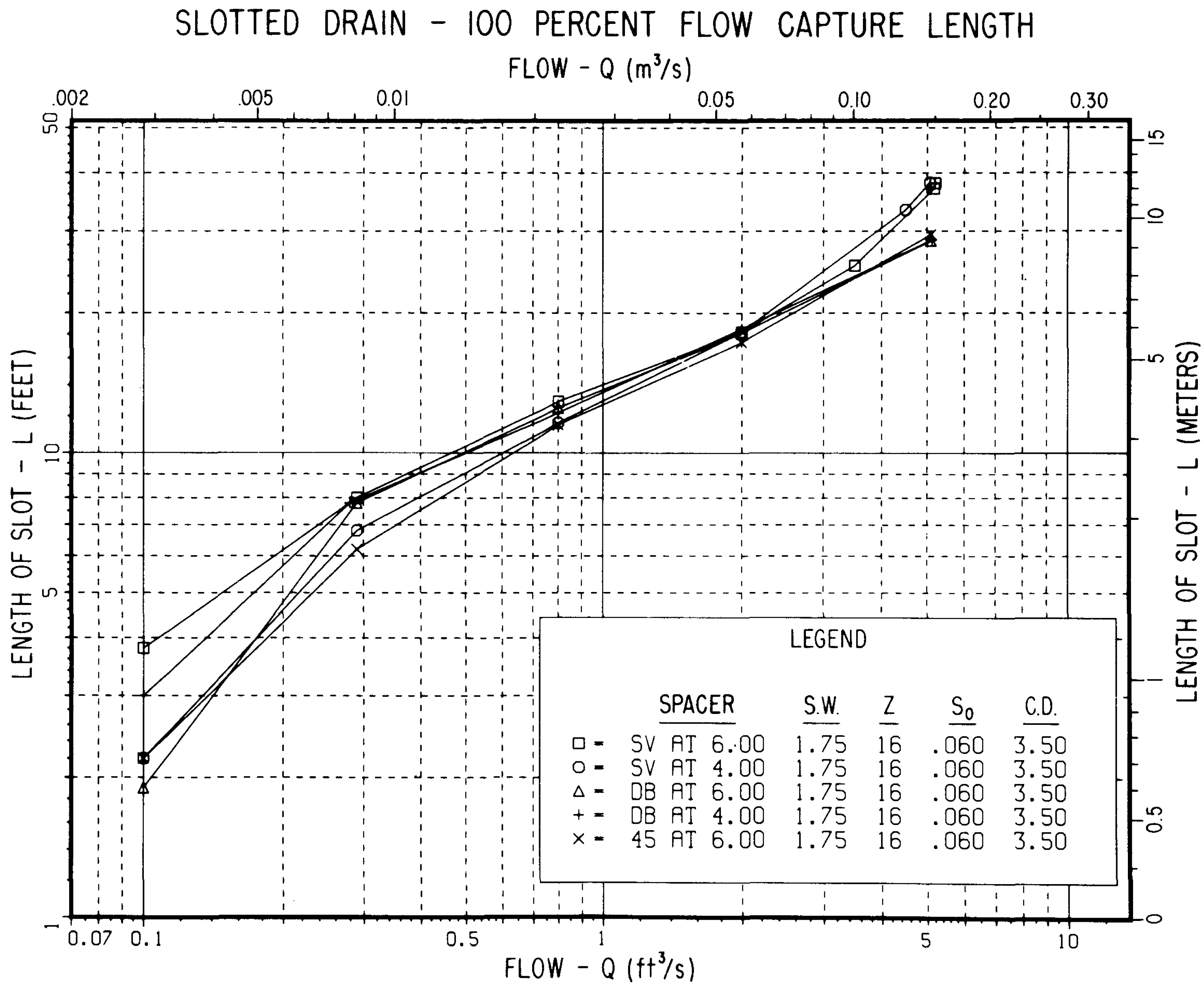


Figure 34. - Spacer type and spacing effect (log-log) Z = 16, So = 0.06.

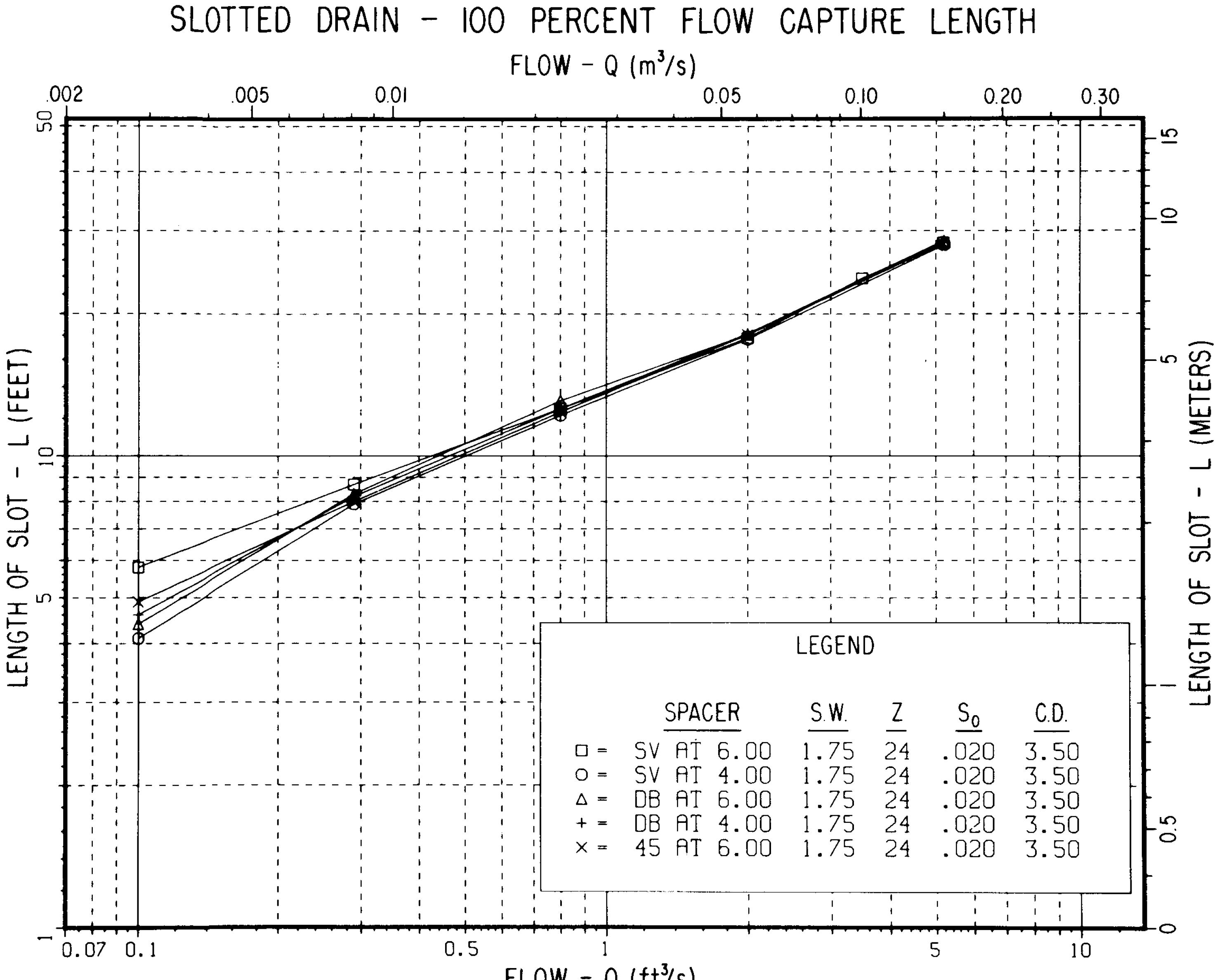


Figure 35. - Spacer type and spacing effect (log-log) Z = 24, So = 0.02.

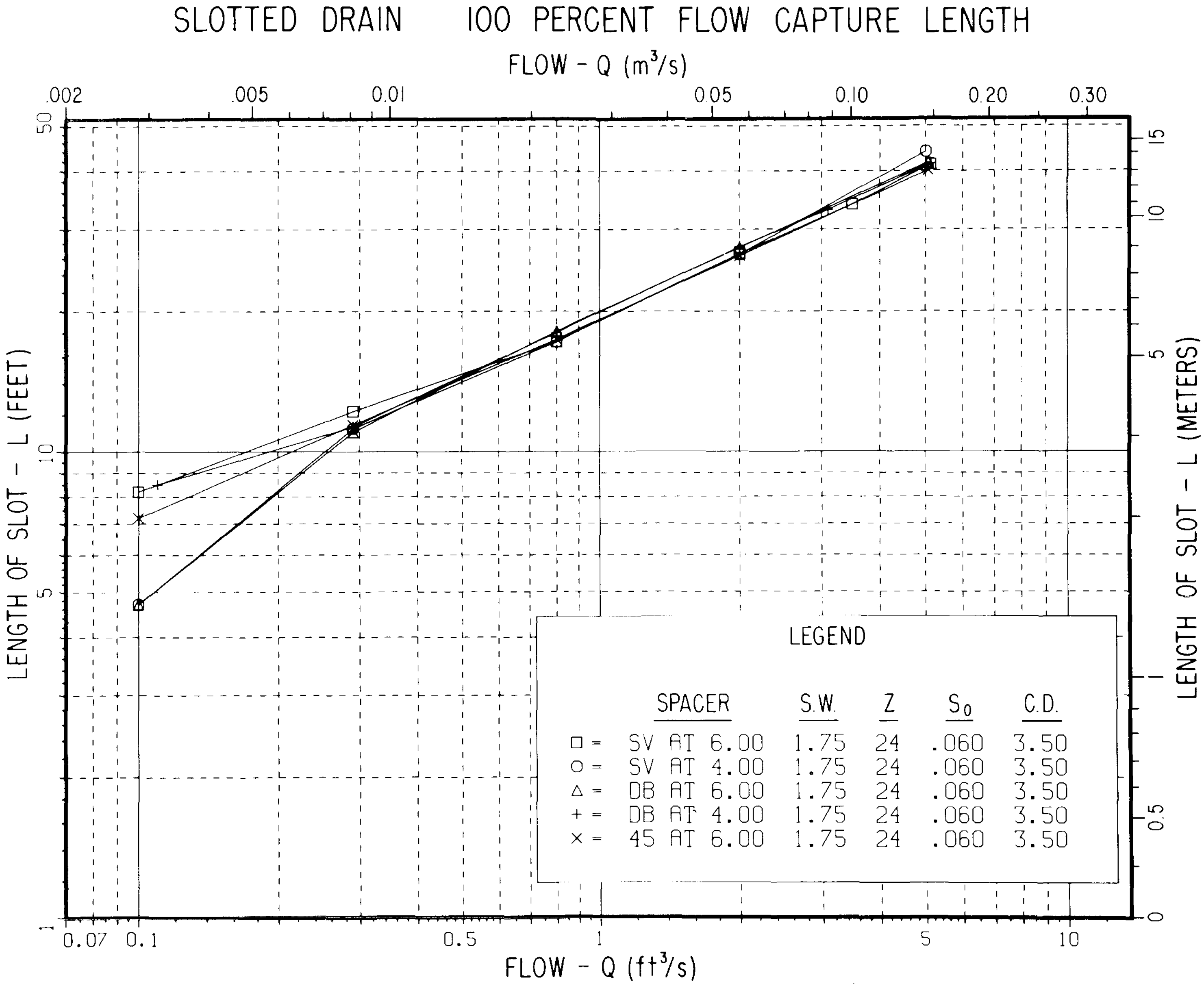


Figure 36. - Spacer type and spacing effect (log-log) Z = 24, So = 0.06.

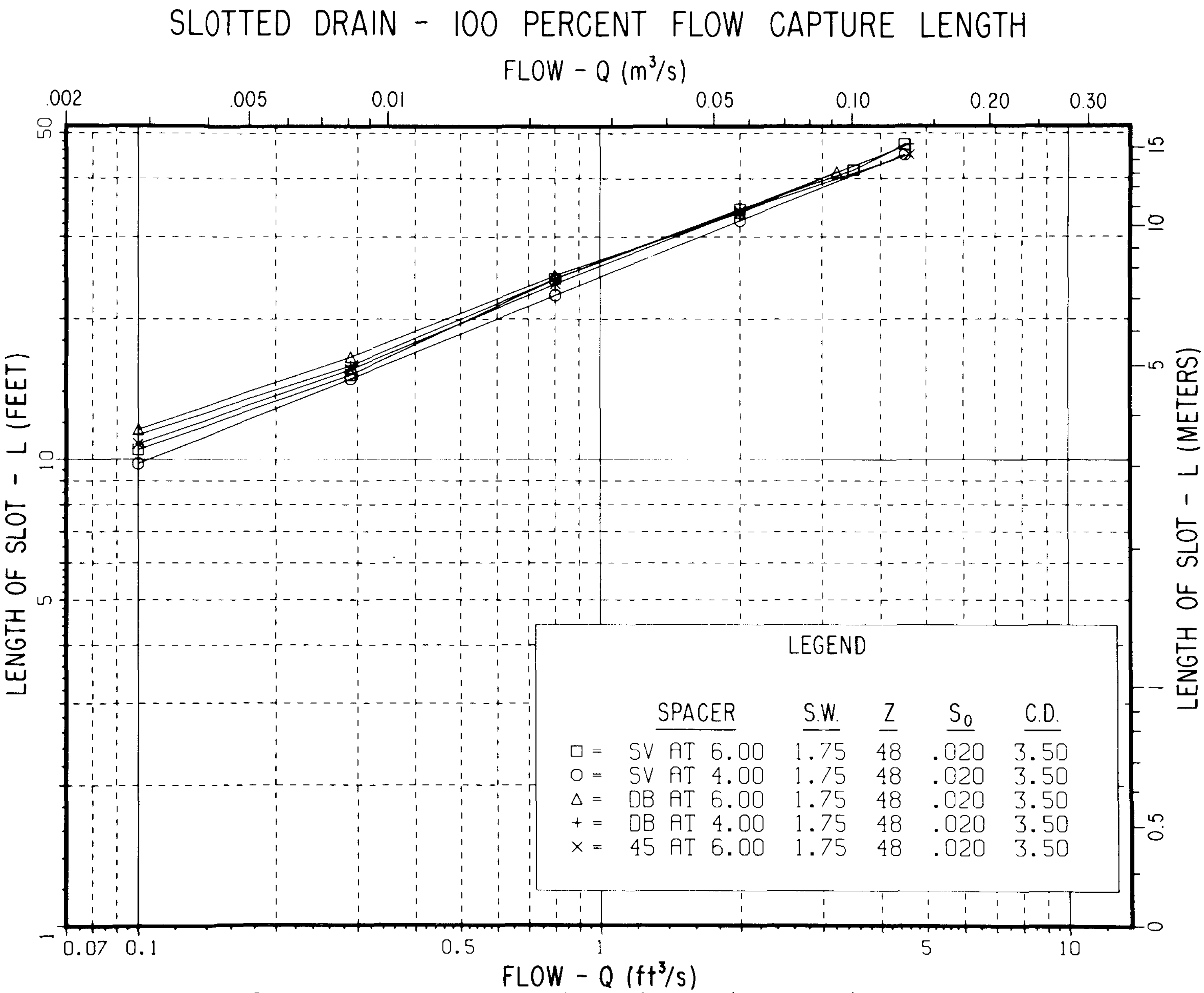


Figure 37. - Spacer type and spacing effect (log-log) Z = 48, So = 0.02.

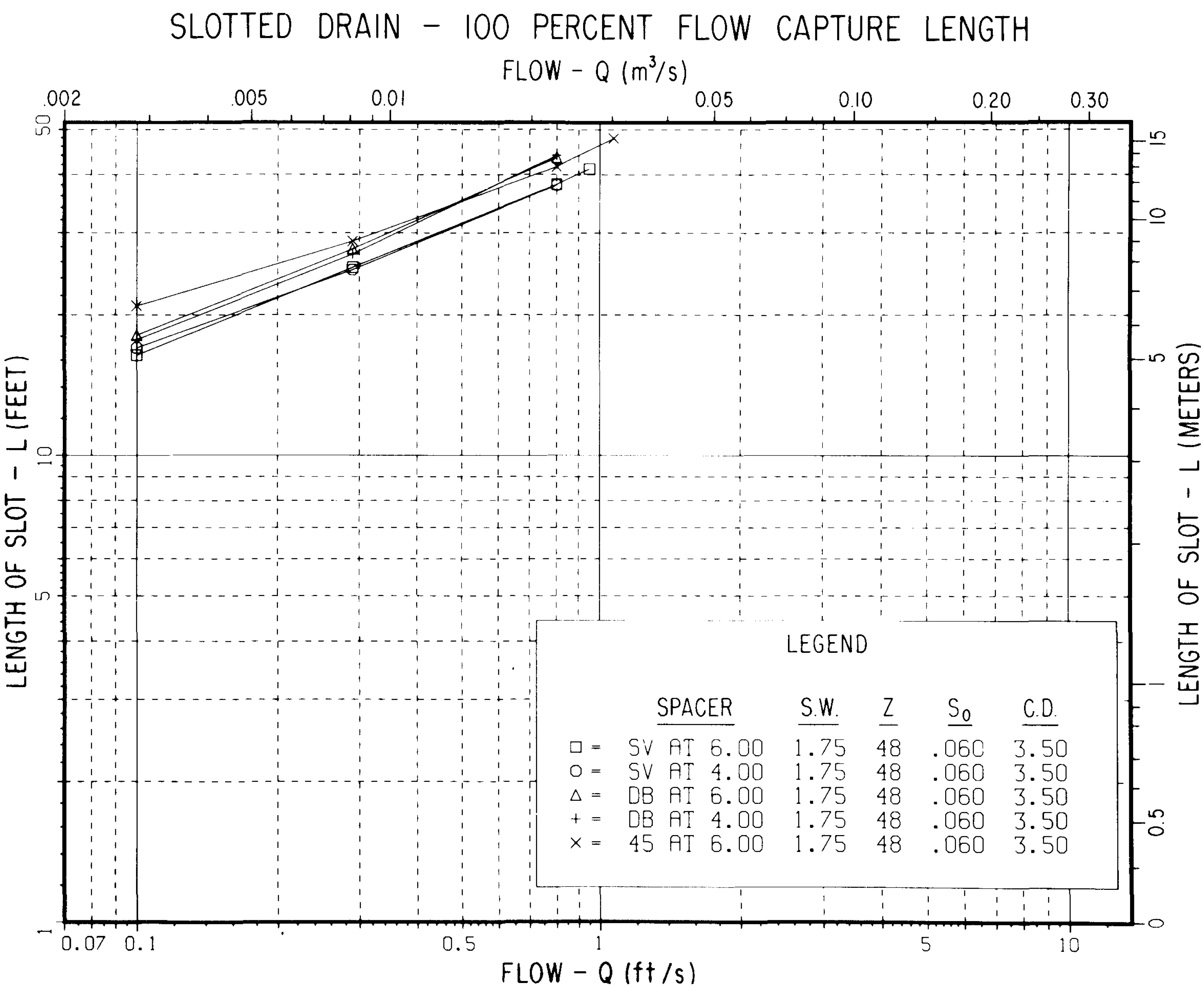
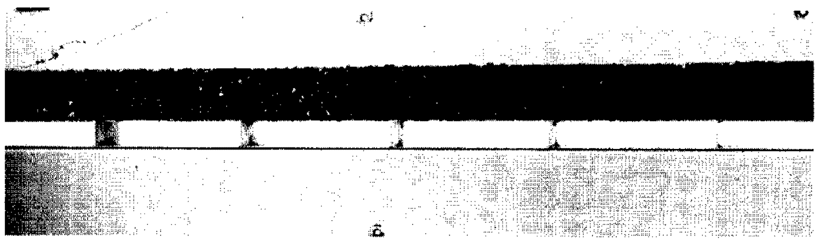
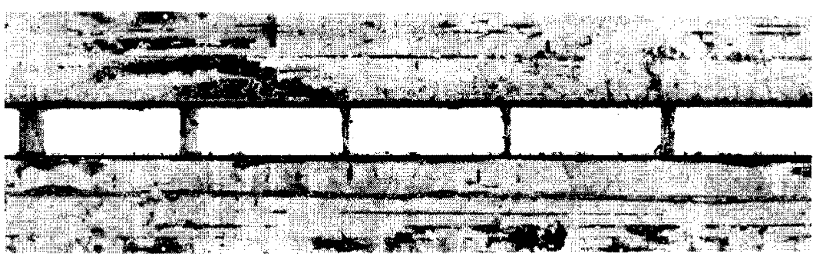


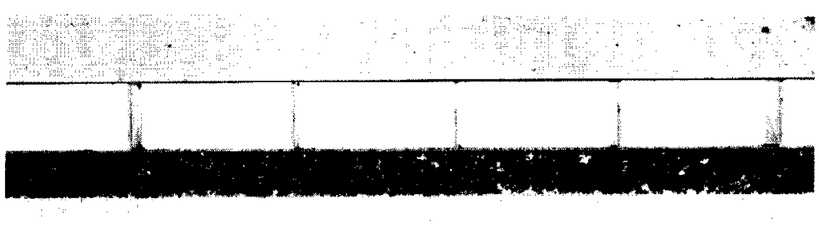
Figure 38. - Spacer type and spacing effect (log-log) Z = 48, So = 0.06.



a. SV-1.00-6.



b. SV-1.75-6.



c. SV-2.50-6.

Figure 39. - Test slots used for slot width tests (top view).

SLOTTED DRAIN - 100 PERCENT FLOW CAPTURE LENGTH

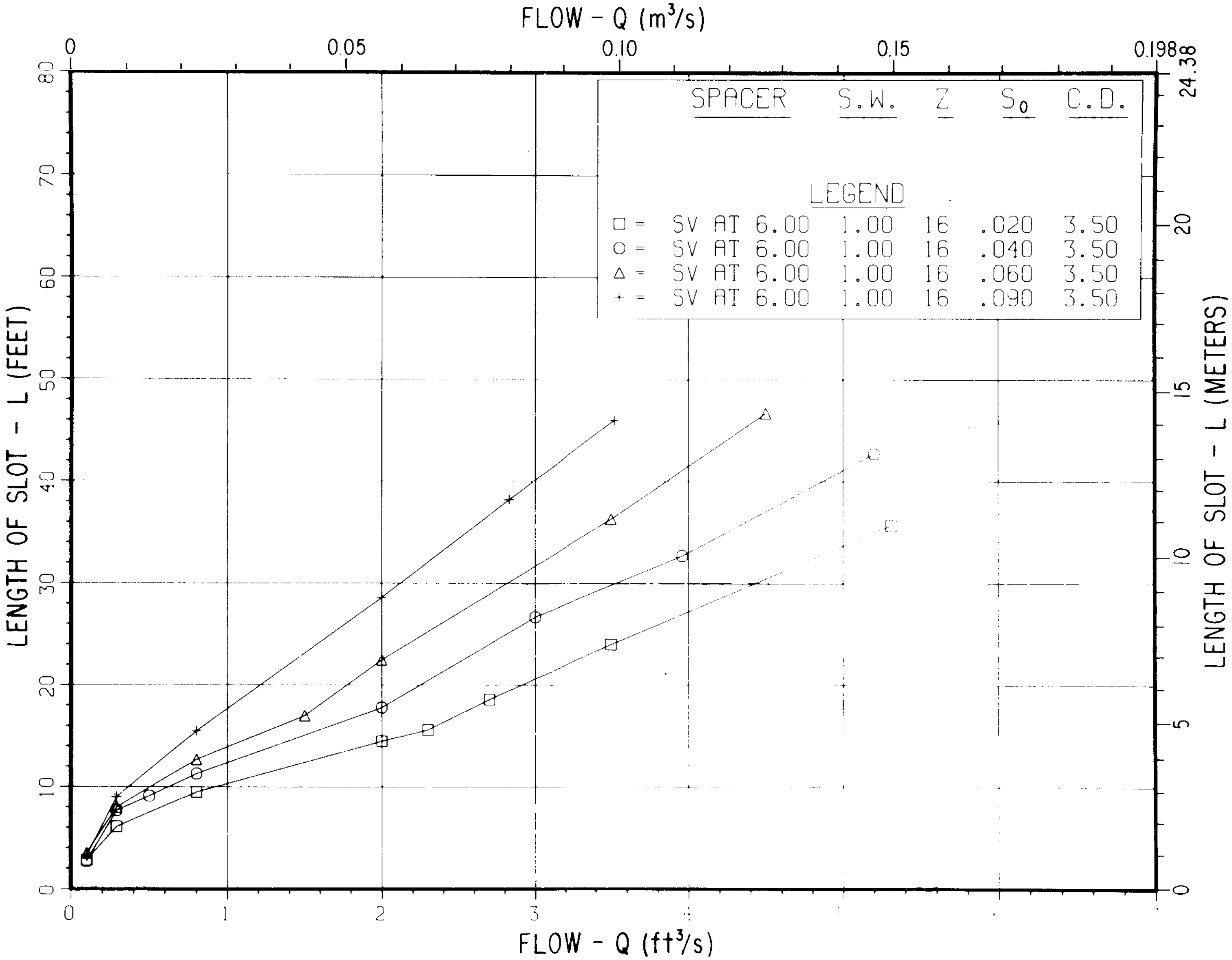


Figure 40. - 100 percent flow capture length for SV-1-6-3.5 at Z = 16.

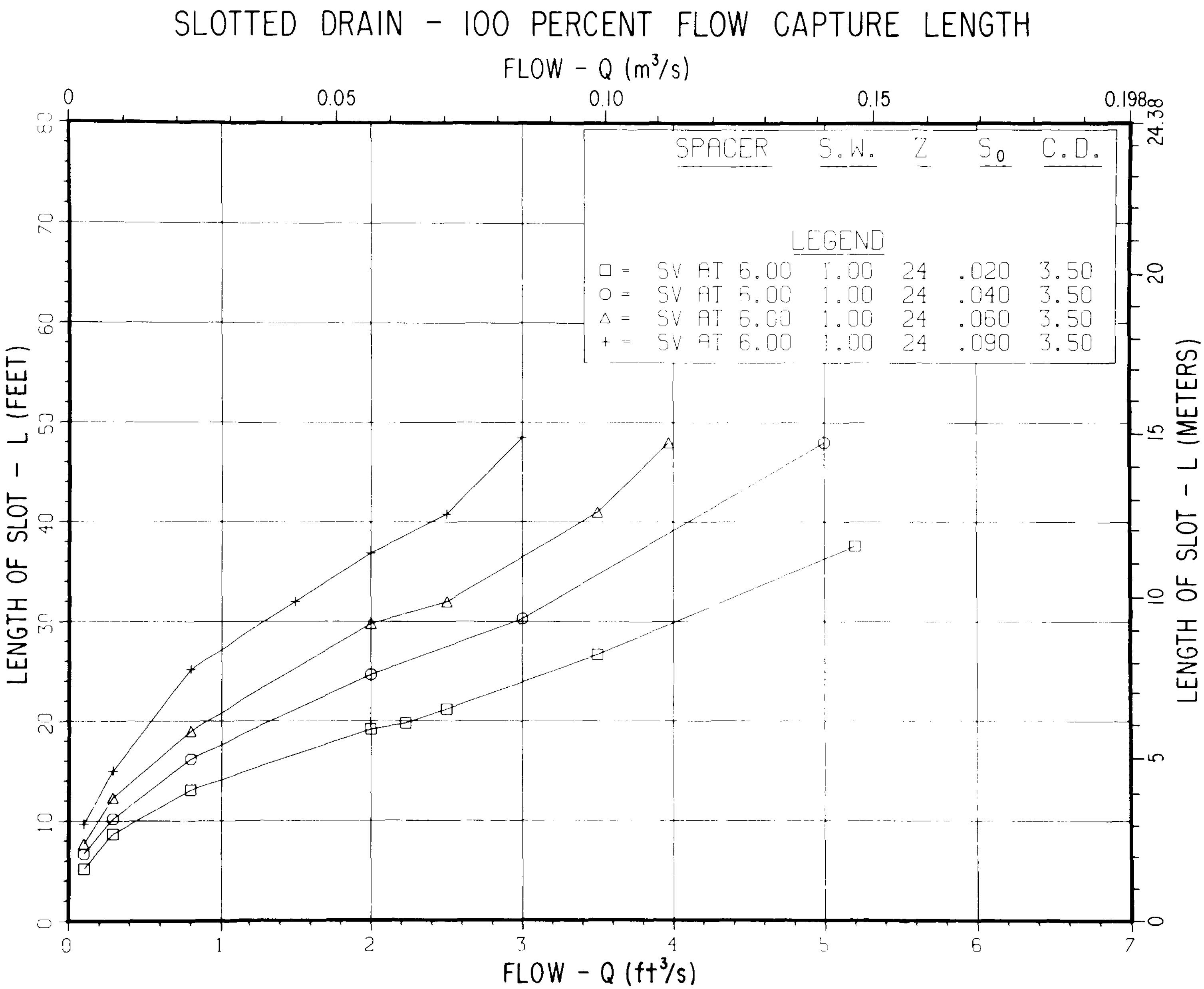


Figure 41. - 100 percent flow capture length for SV-1-6-3.5 at Z = 24.

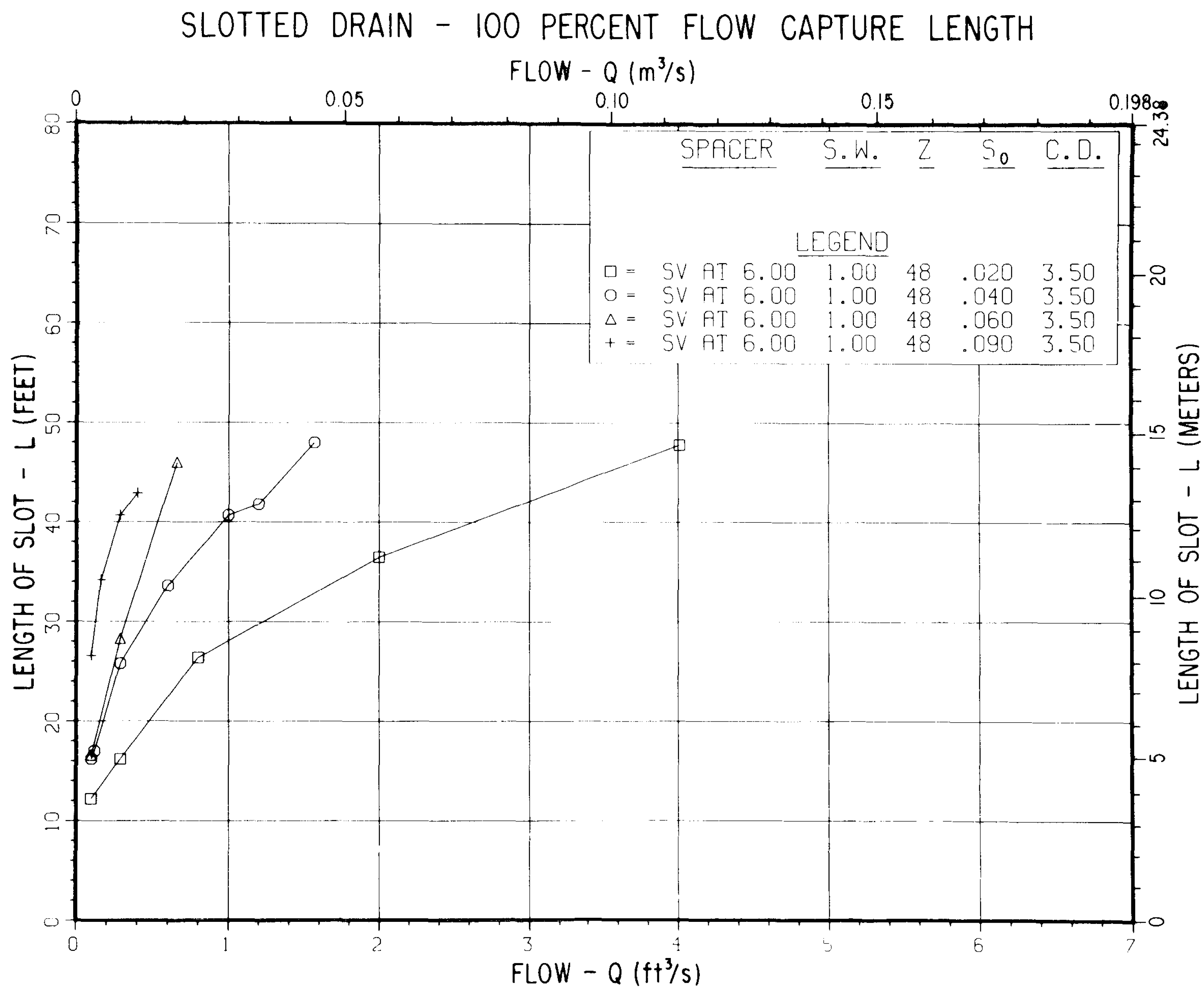


Figure 42. - 100 percent flow capture length for SV-1-6-3.5 at Z = 48.

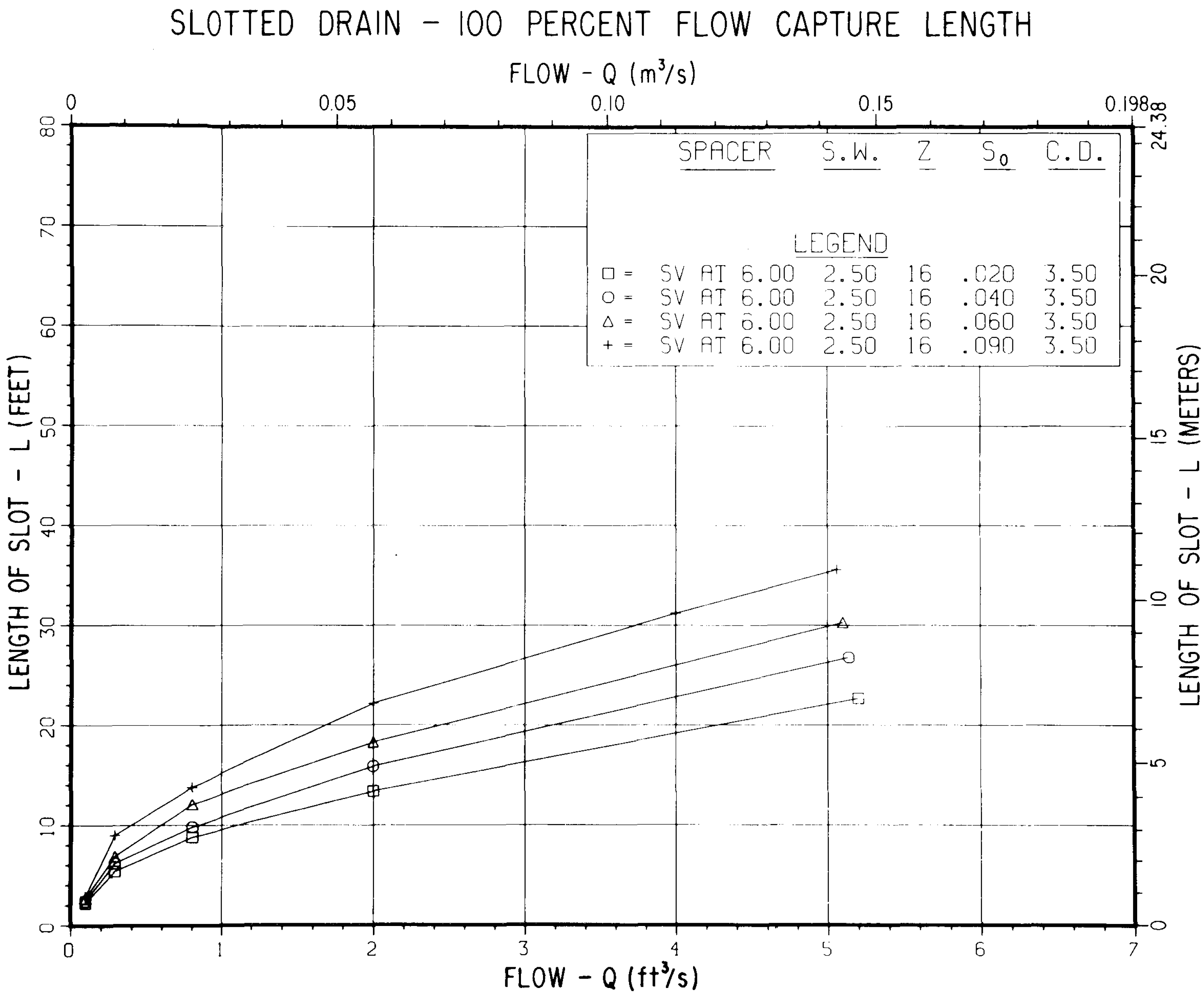


Figure 43. - 100 percent flow capture length for SV-2.5-6-3.5 at Z = 16.

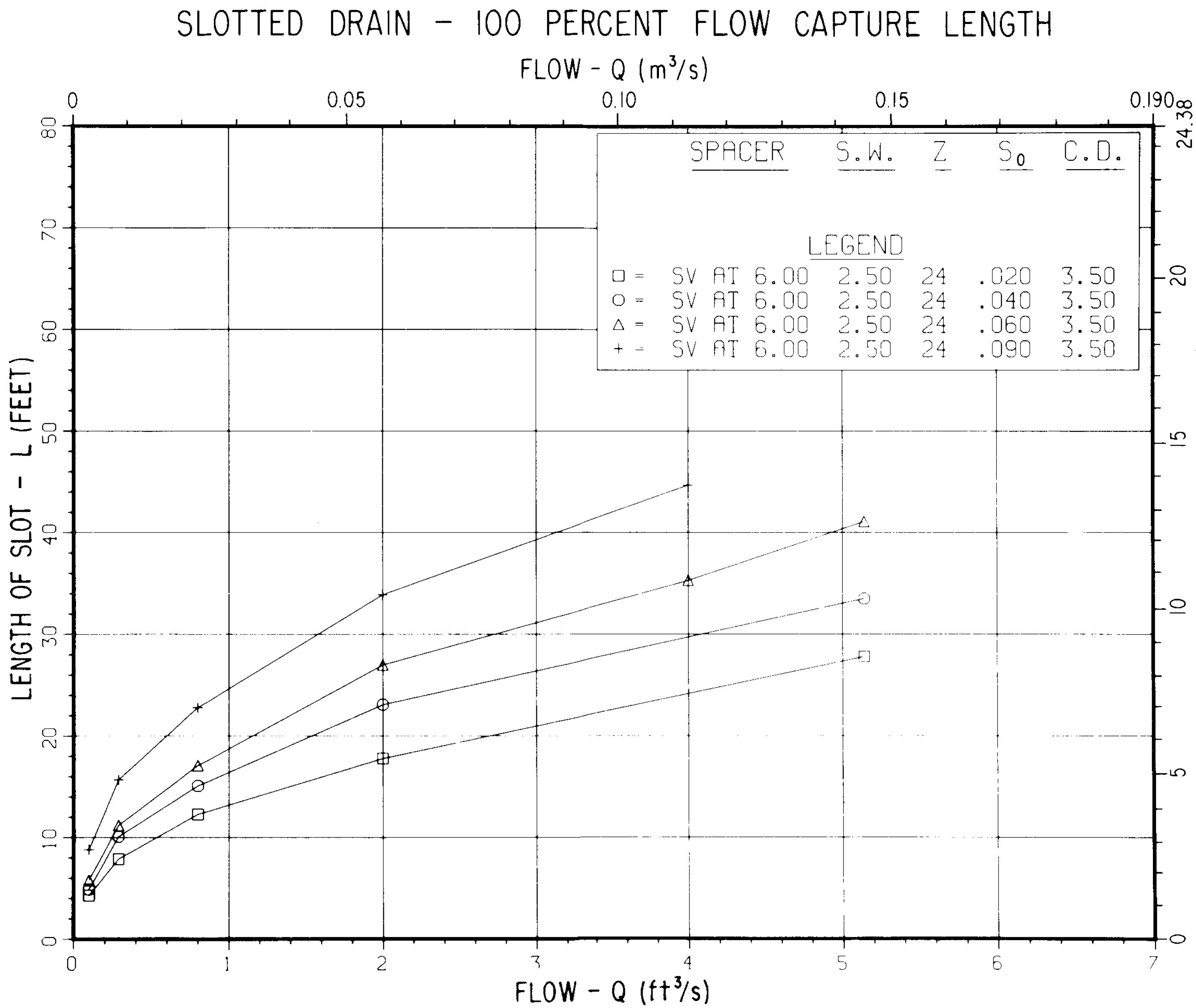


Figure 44. - 100 percent flow capture length for SV-2.5-6-3.5 at Z = 24.

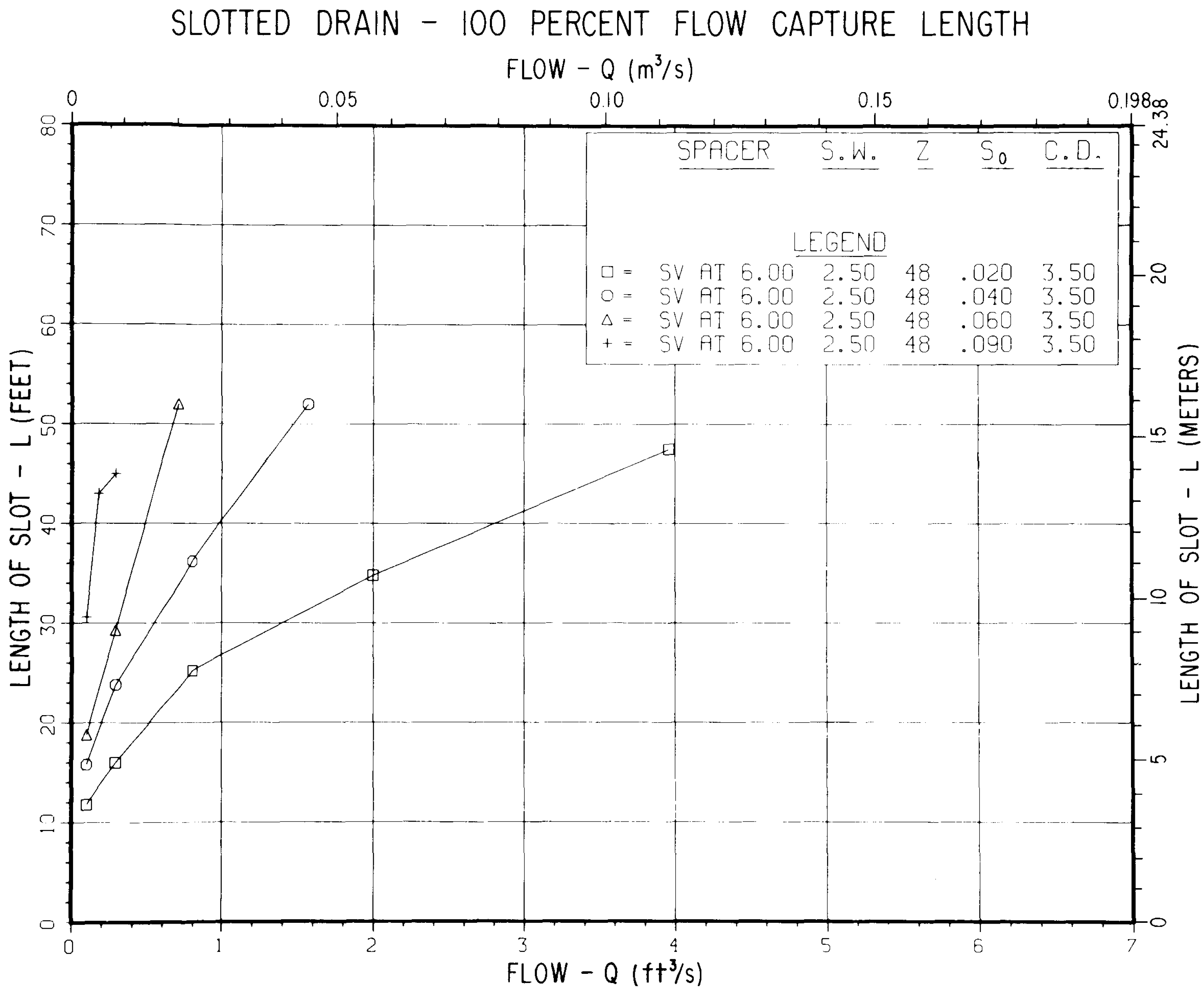


Figure 45. - 100 percent flow capture length for SV-2.5-6-3.5 at Z = 48.

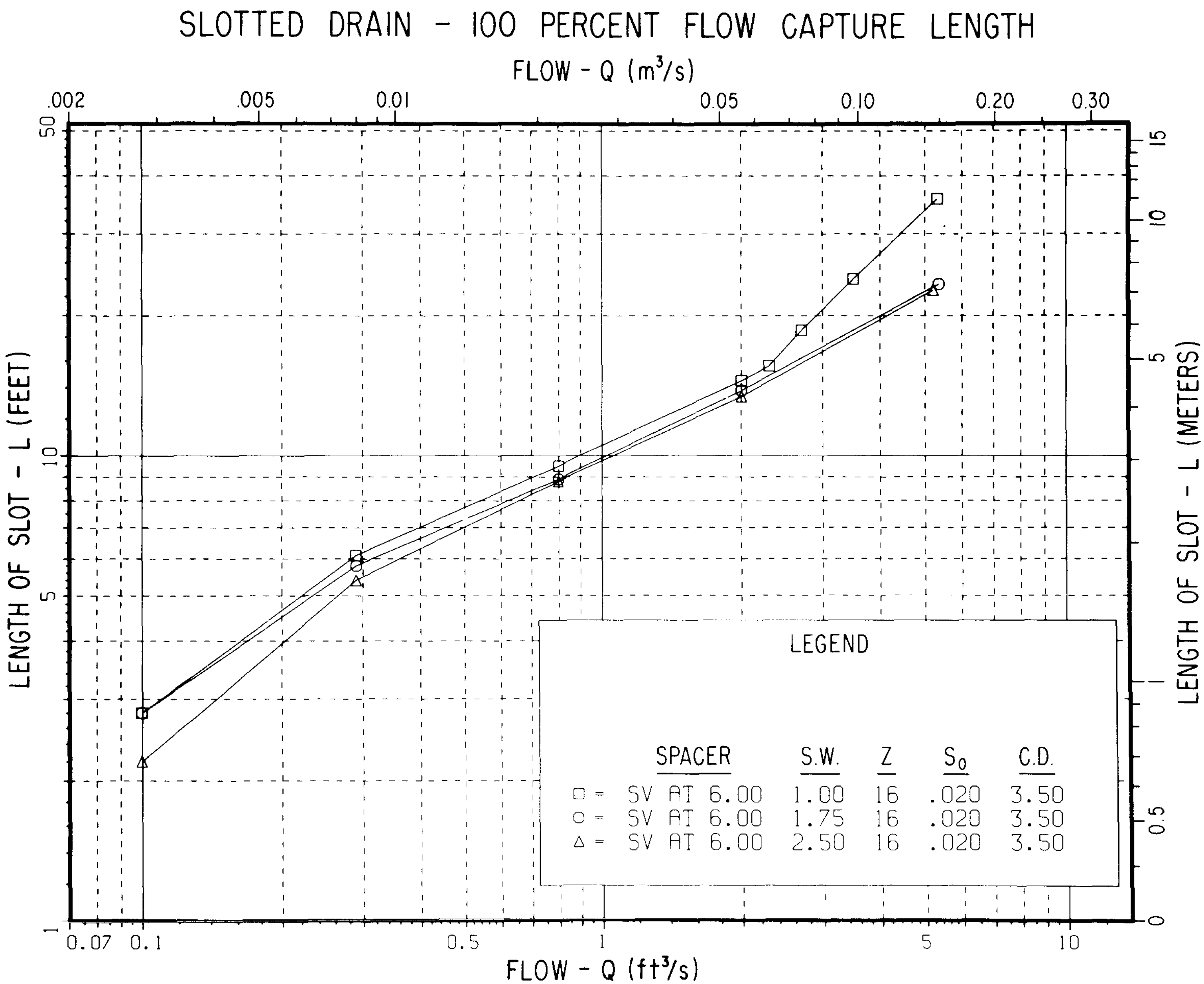


Figure 46. - Slot width effect (log-log) Z = 16, So = 0.02.

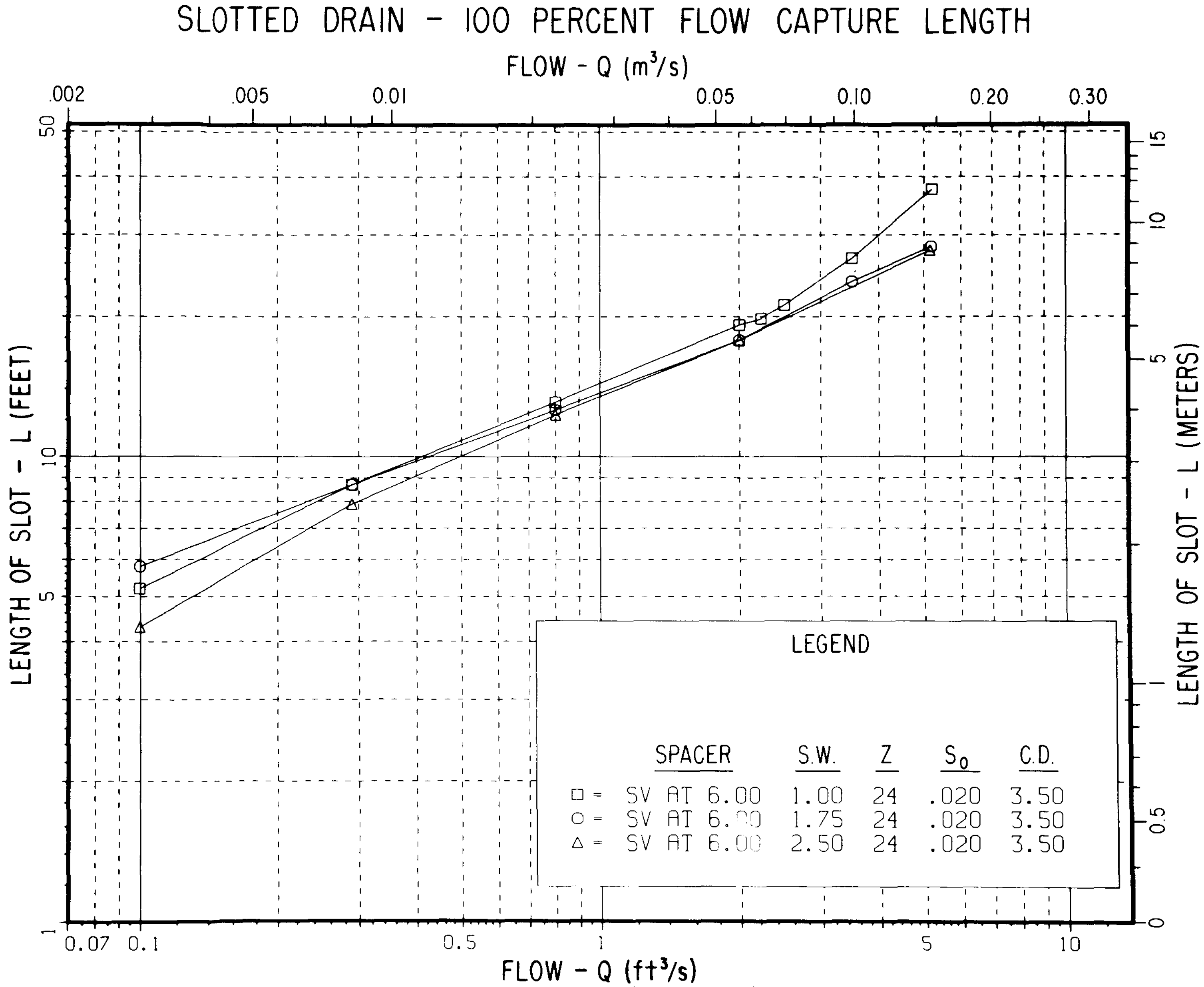


Figure 47. - Slot width effect (log-log) Z = 24, So = 0.02.

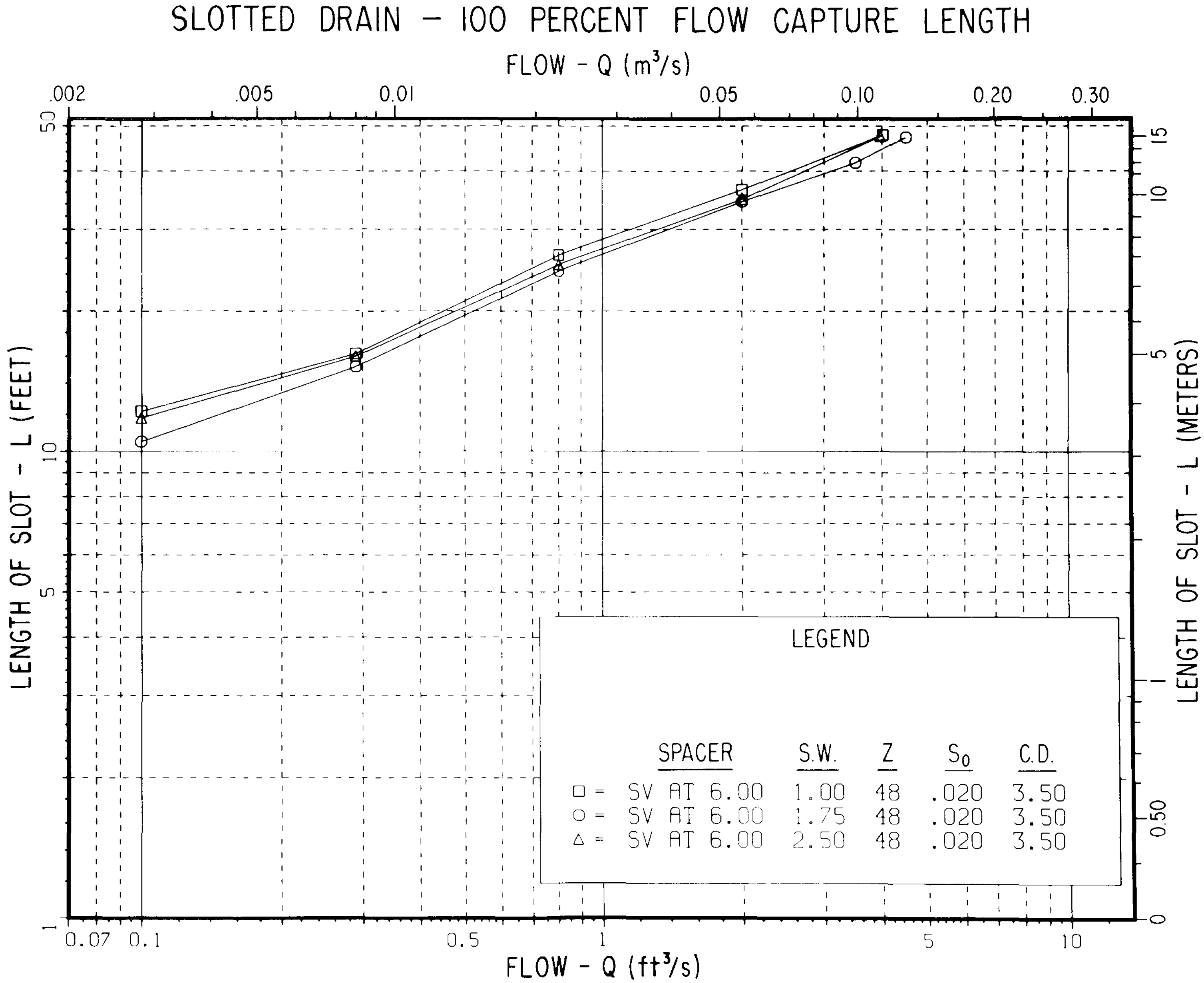


Figure 48. - Slot width effect (log-log) Z = 48, So = 0.02.

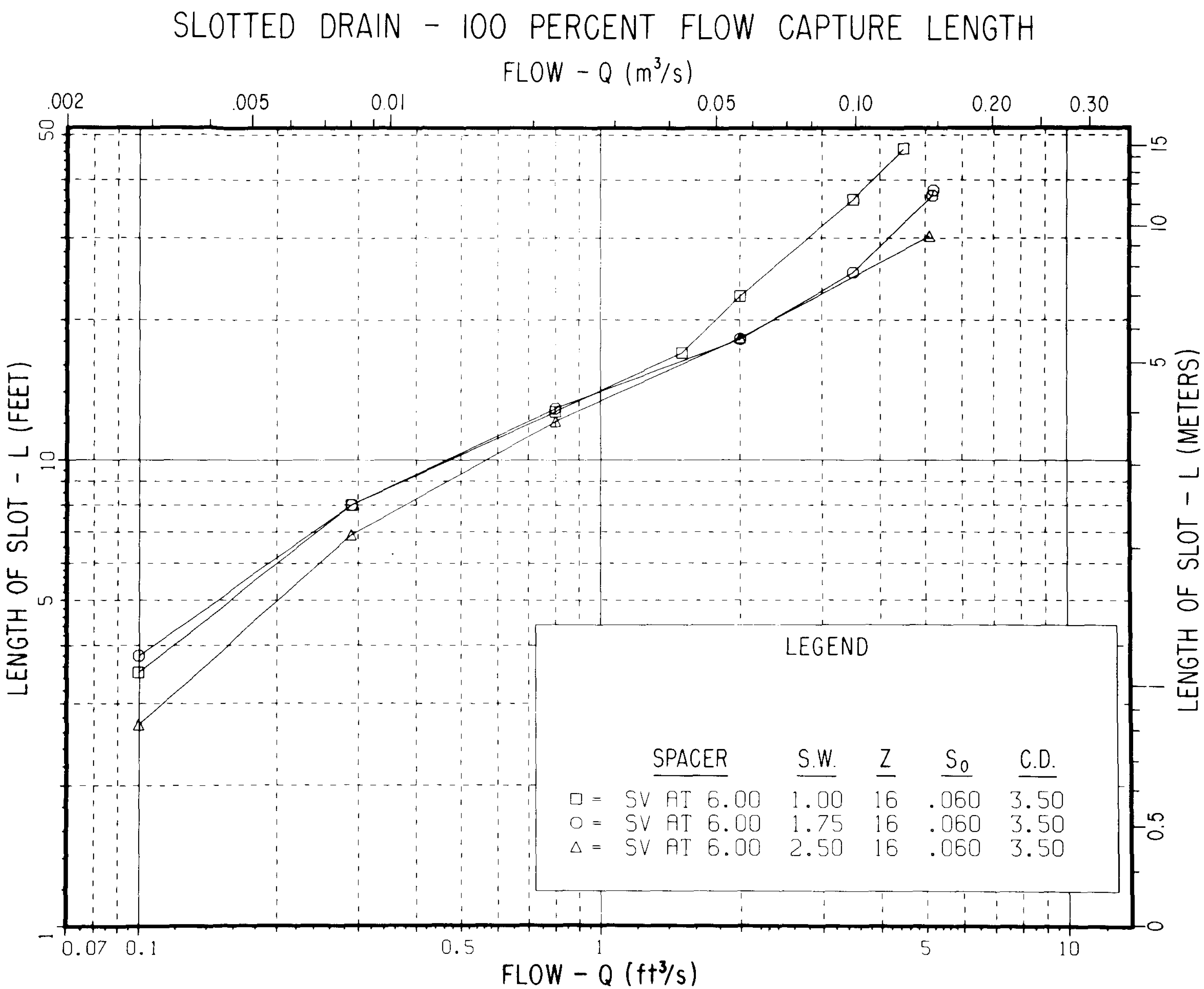


Figure 49. - Slot width effect (log-log) Z = 16, So = 0.06.

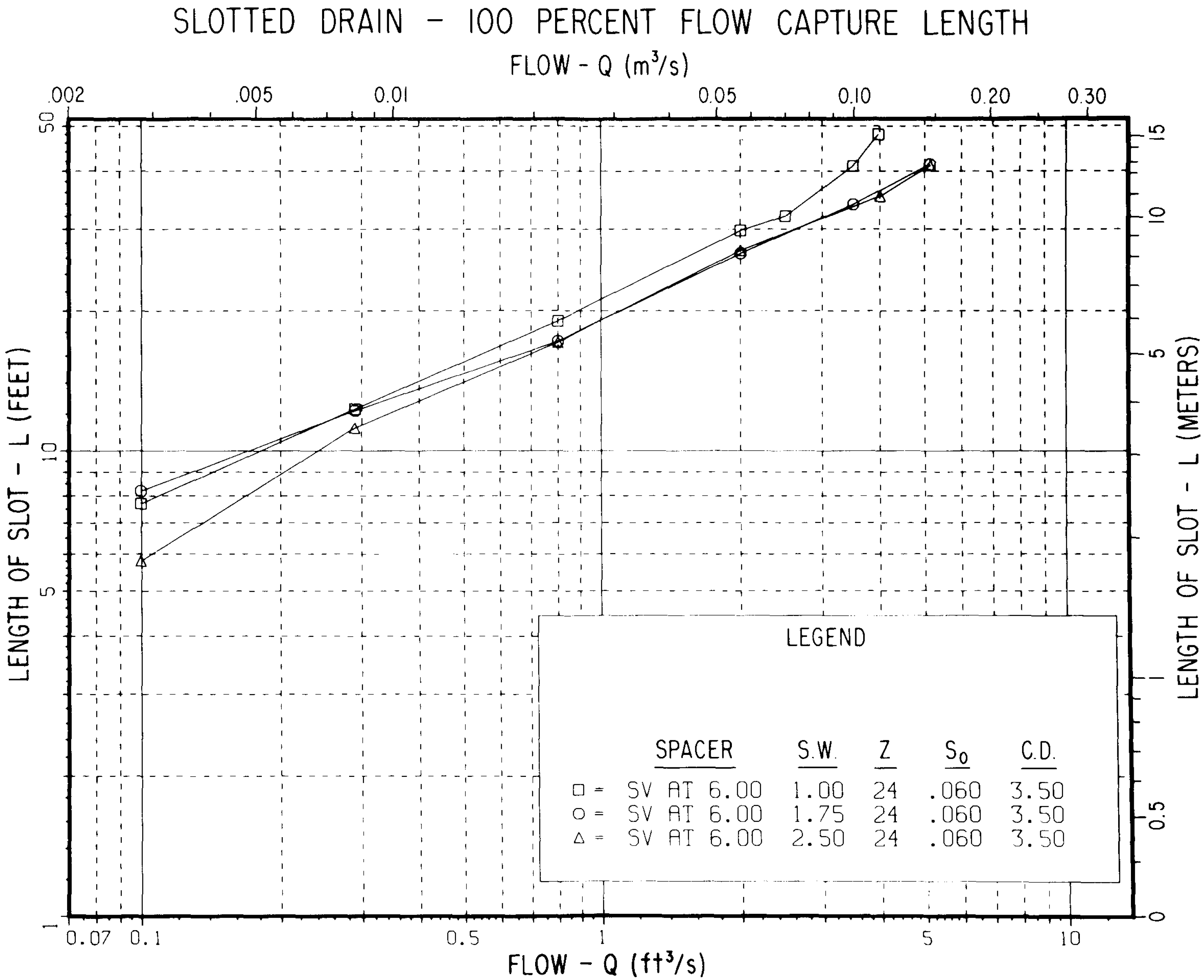


Figure 50. - Slot width effect (log-log) Z = 24, So = 0.06.

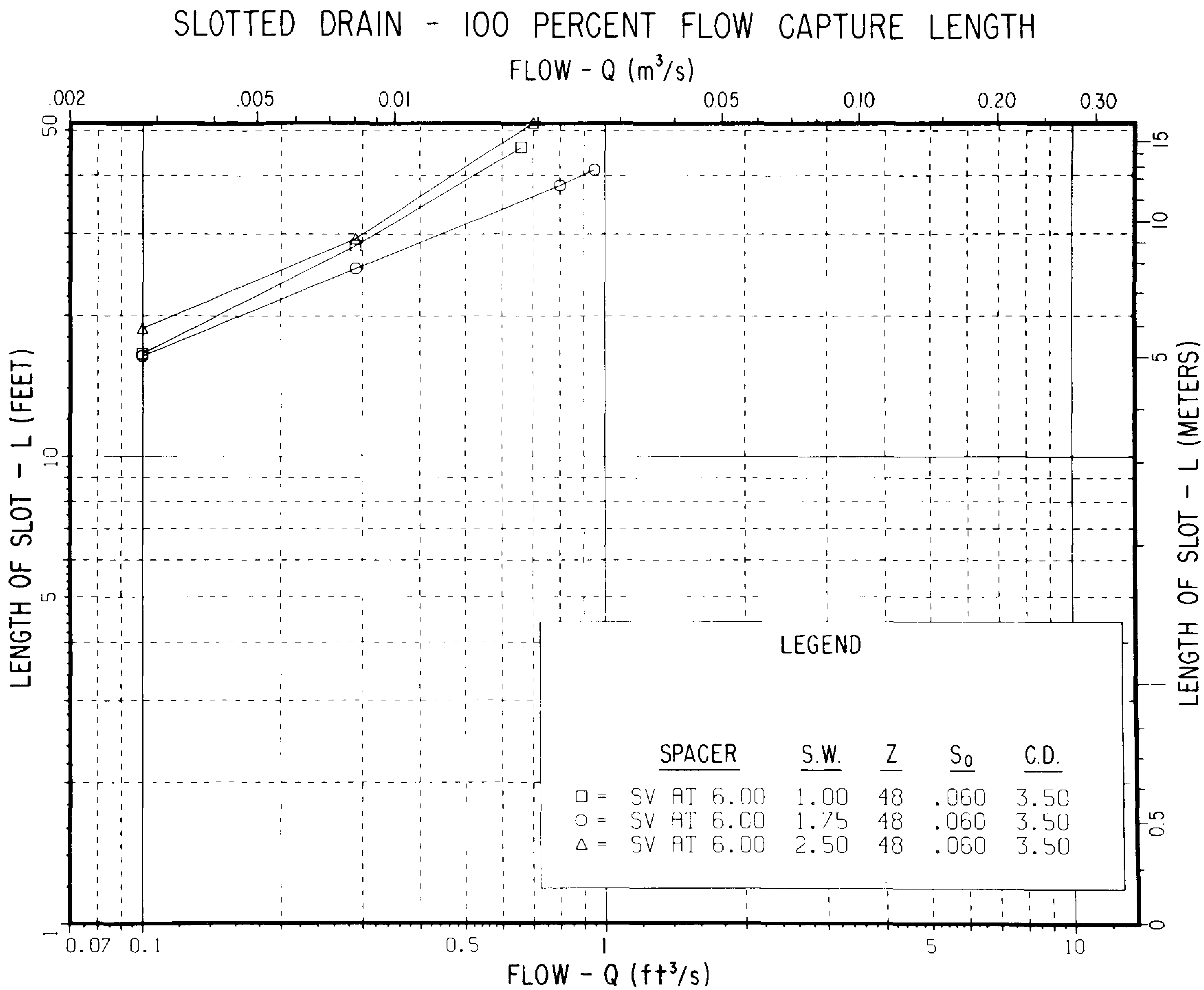


Figure 51. - Slot width effect (log-log) Z = 48, So = 0.09.

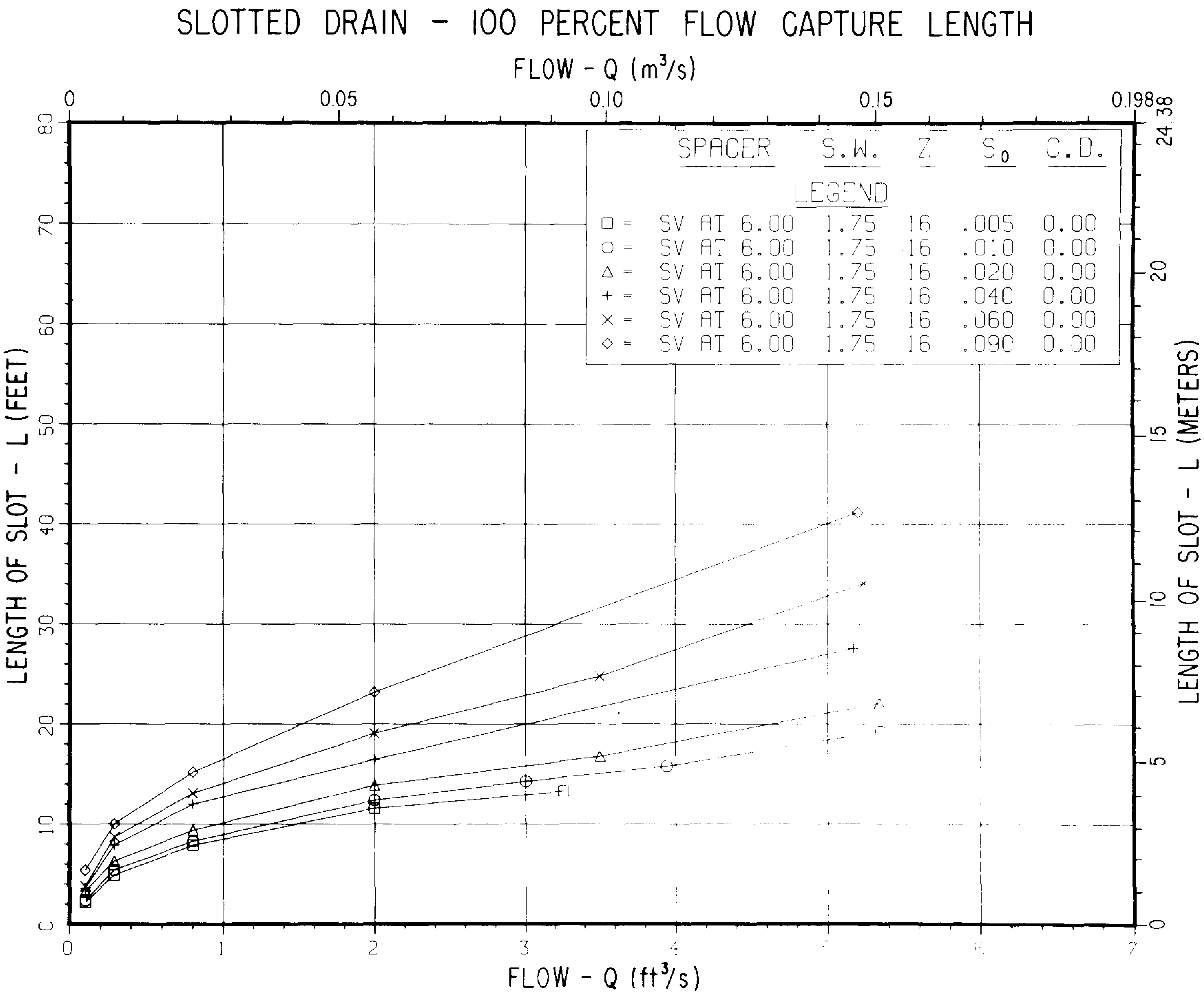


Figure 52. - 100 percent flow capture length for SV-1.75-6-0 at Z = 16.

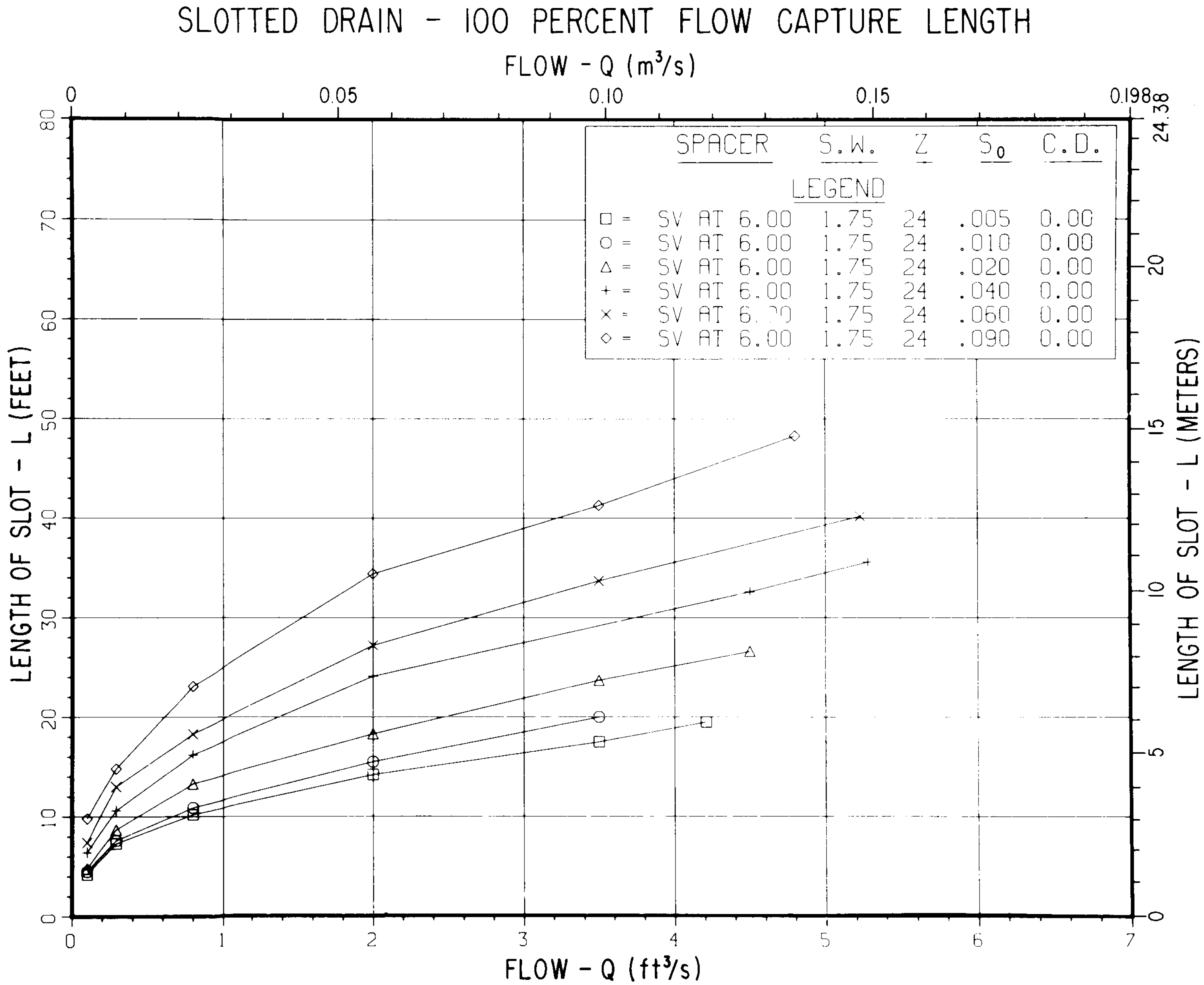


Figure 53. - 100 percent flow capture length for SV-1.75-6-0 at Z = 24.

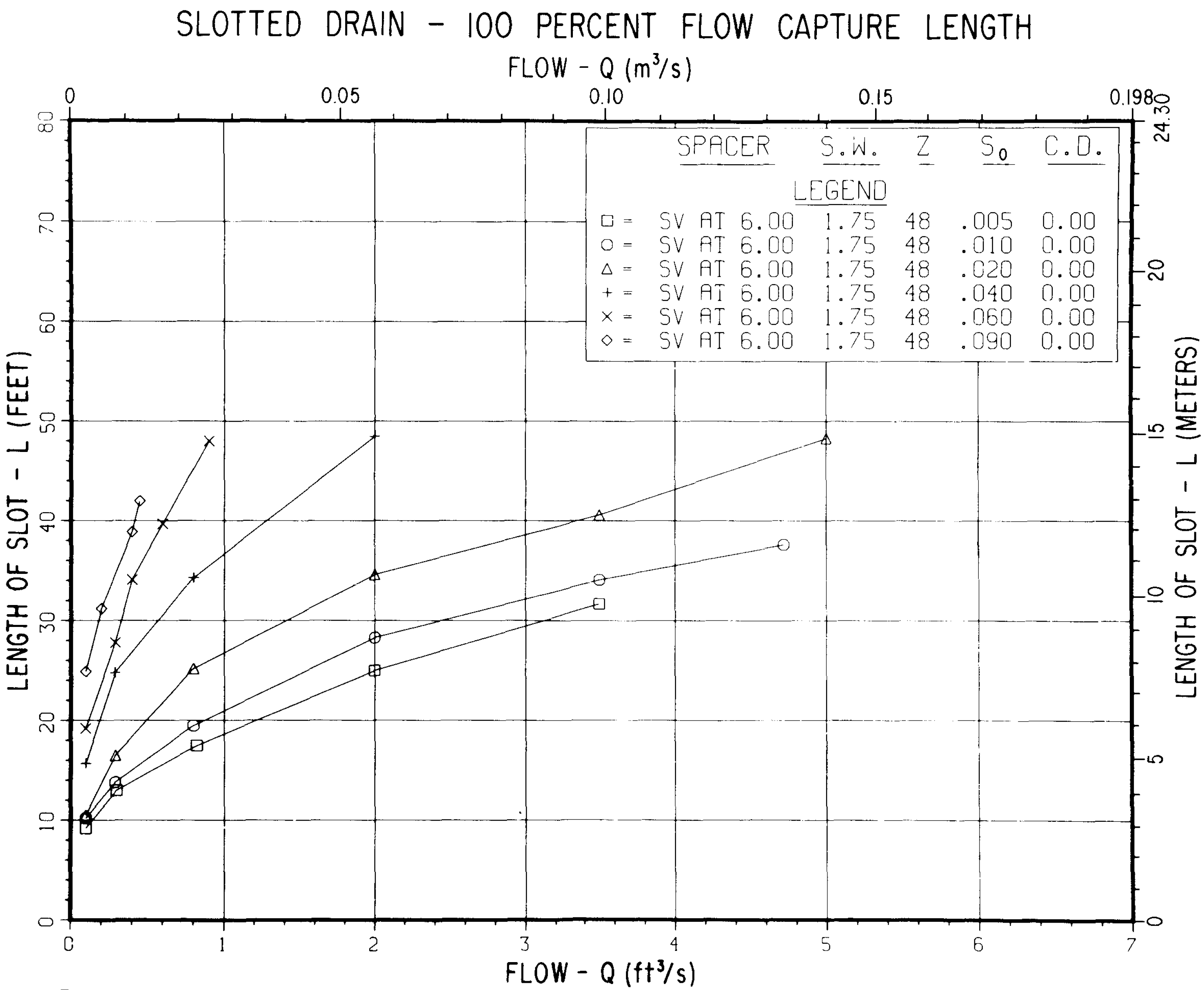


Figure 54. - 100 percent flow capture length for SV-1.75-6-0 at Z = 48.

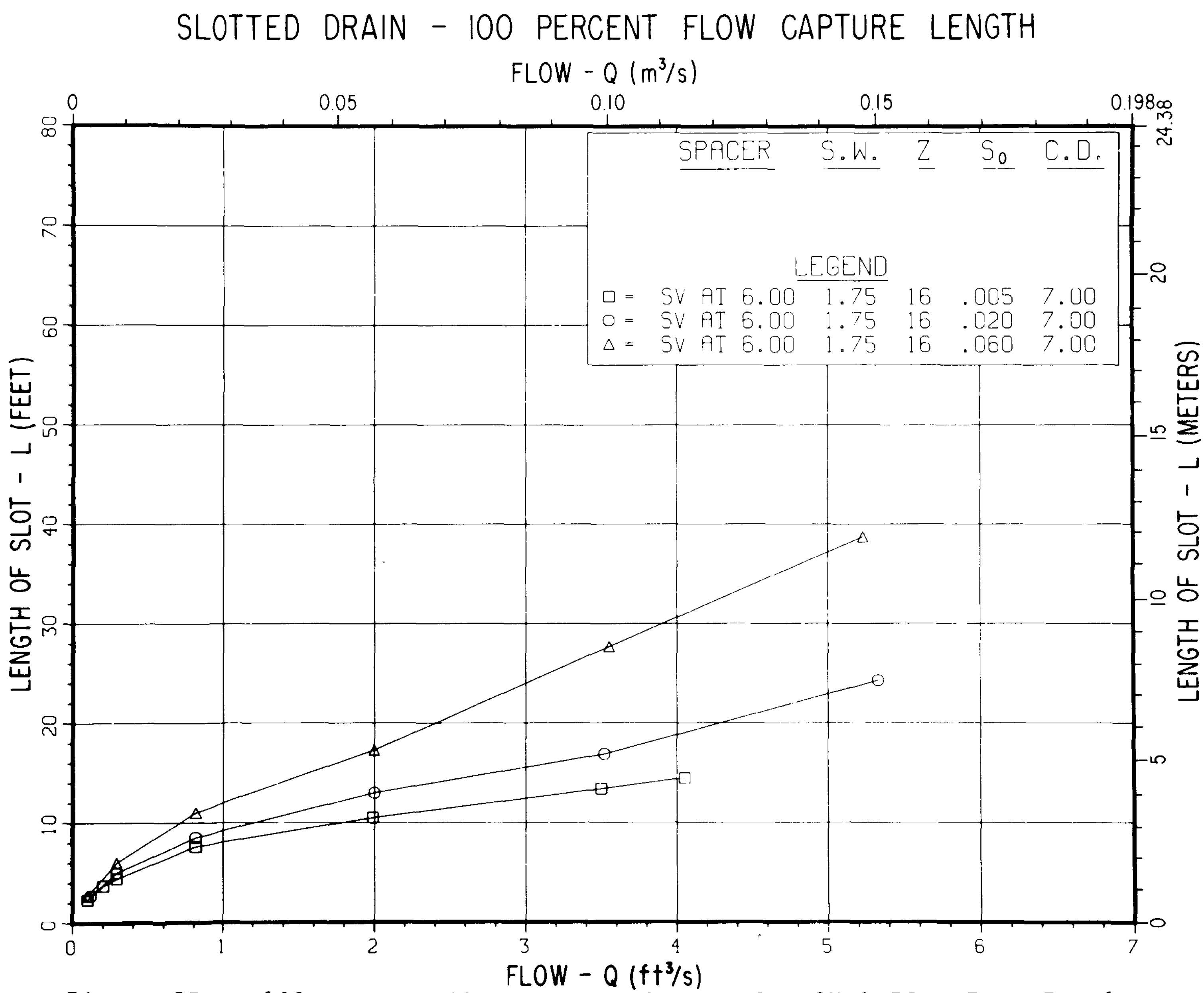


Figure 55. - 100 percent flow capture length for SV-1.75-6-7 at Z = 16.

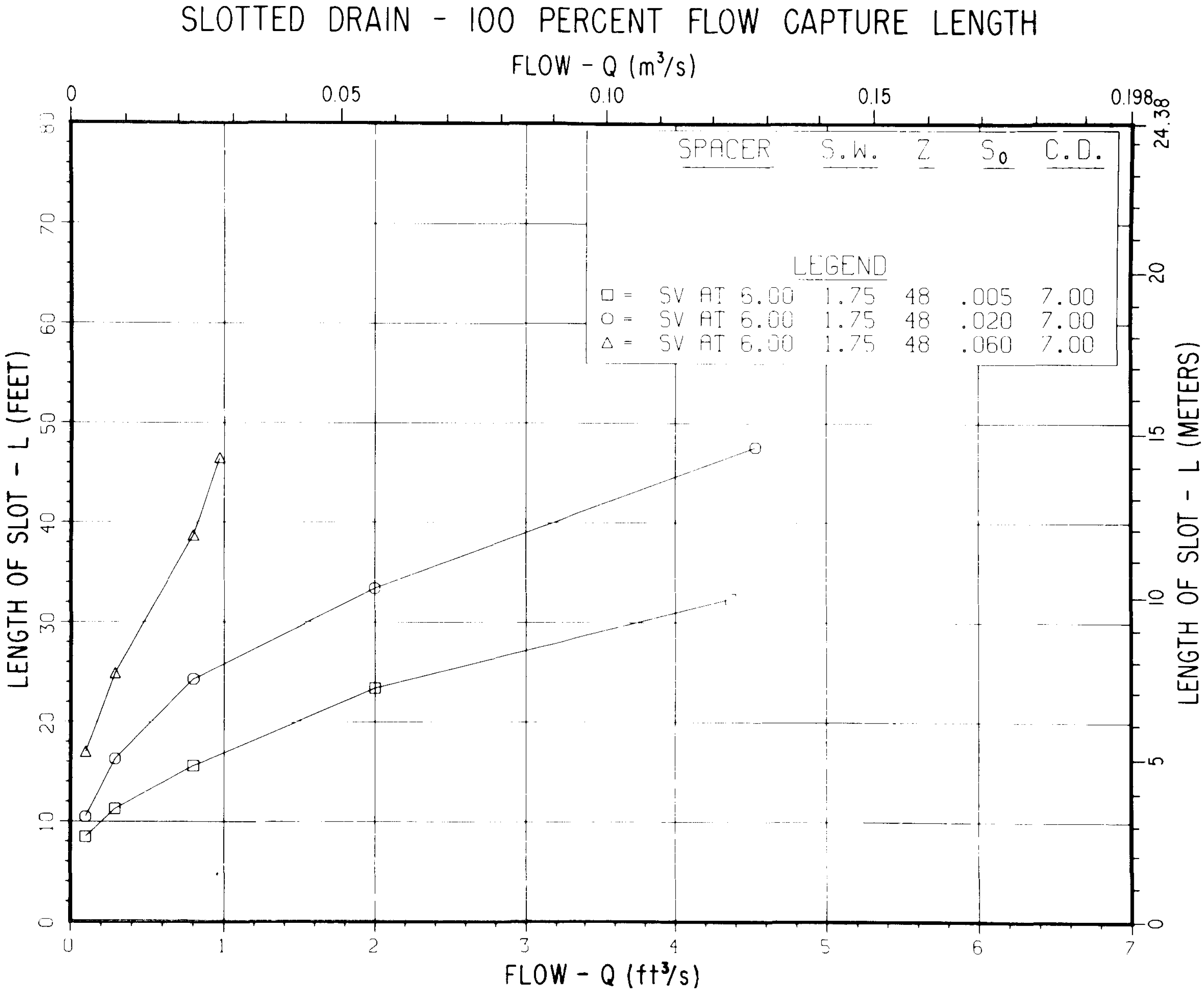


Figure 56. - 100 percent flow capture length for SV-1.75-6-7 at Z = 48.

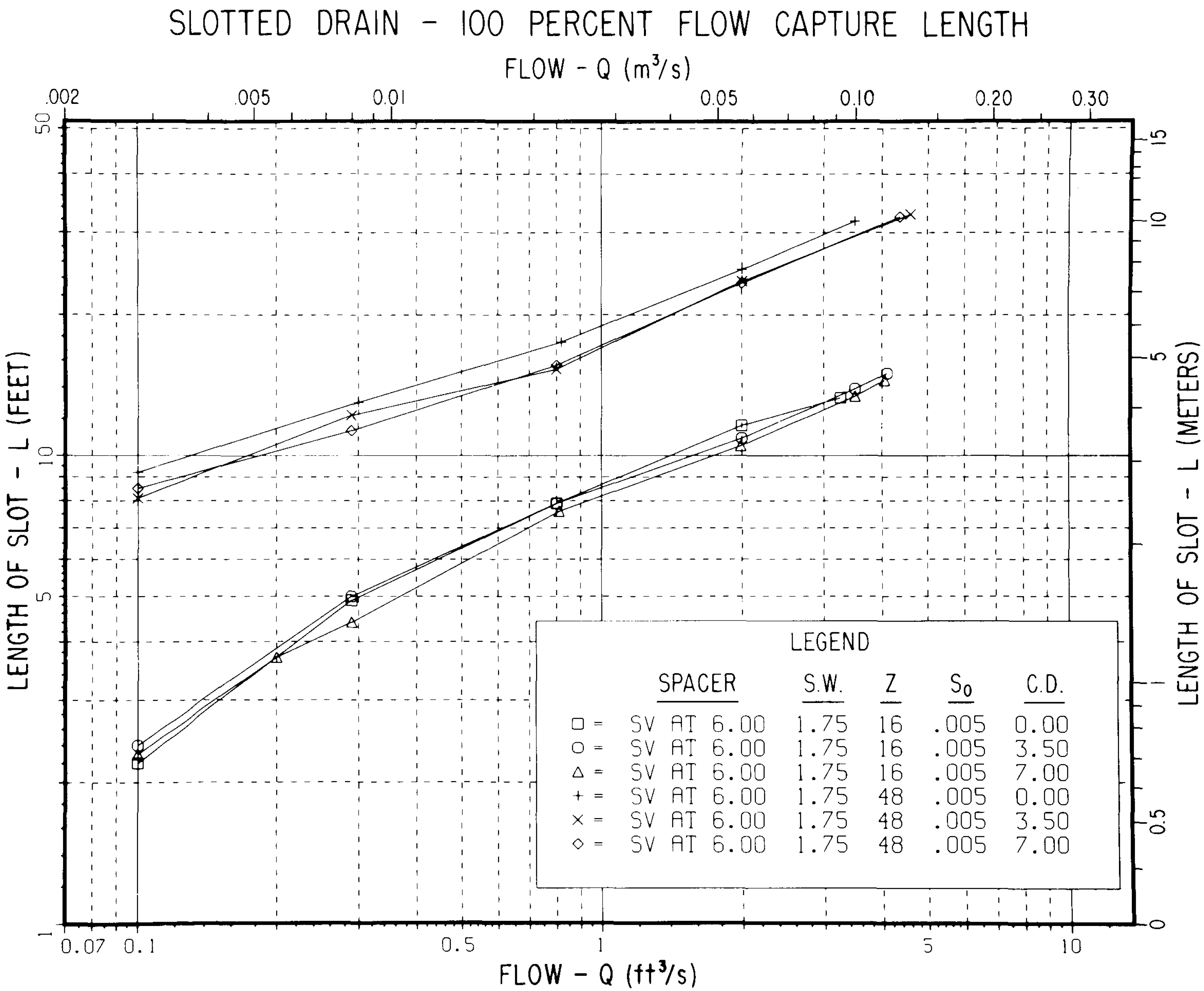


Figure 57. - Curb distance effect (log-log) Z = 16, 48; So = 0.005.

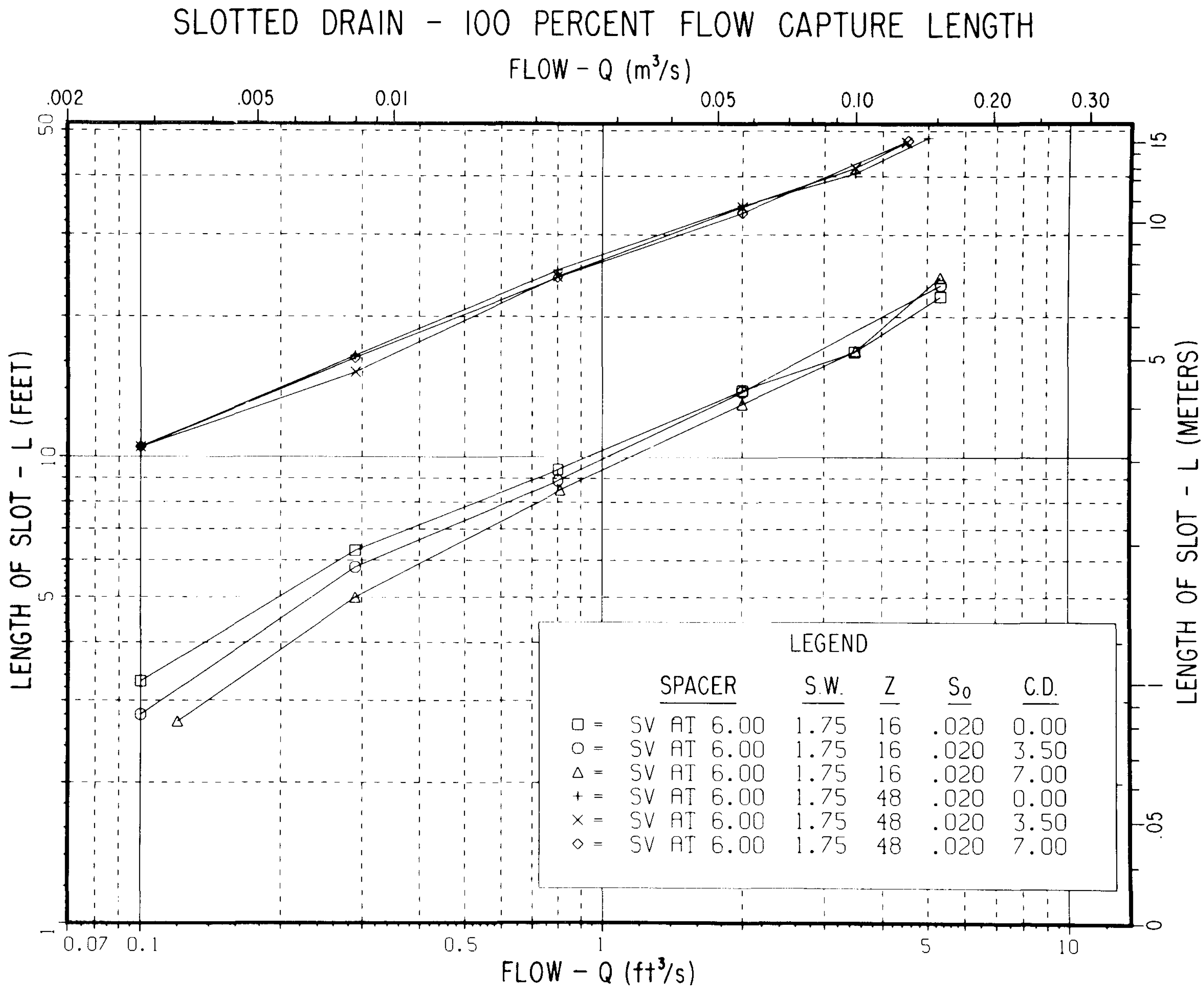


Figure 58. - Curb distance effect (log-log) Z = 16, 48; So = 0.02.

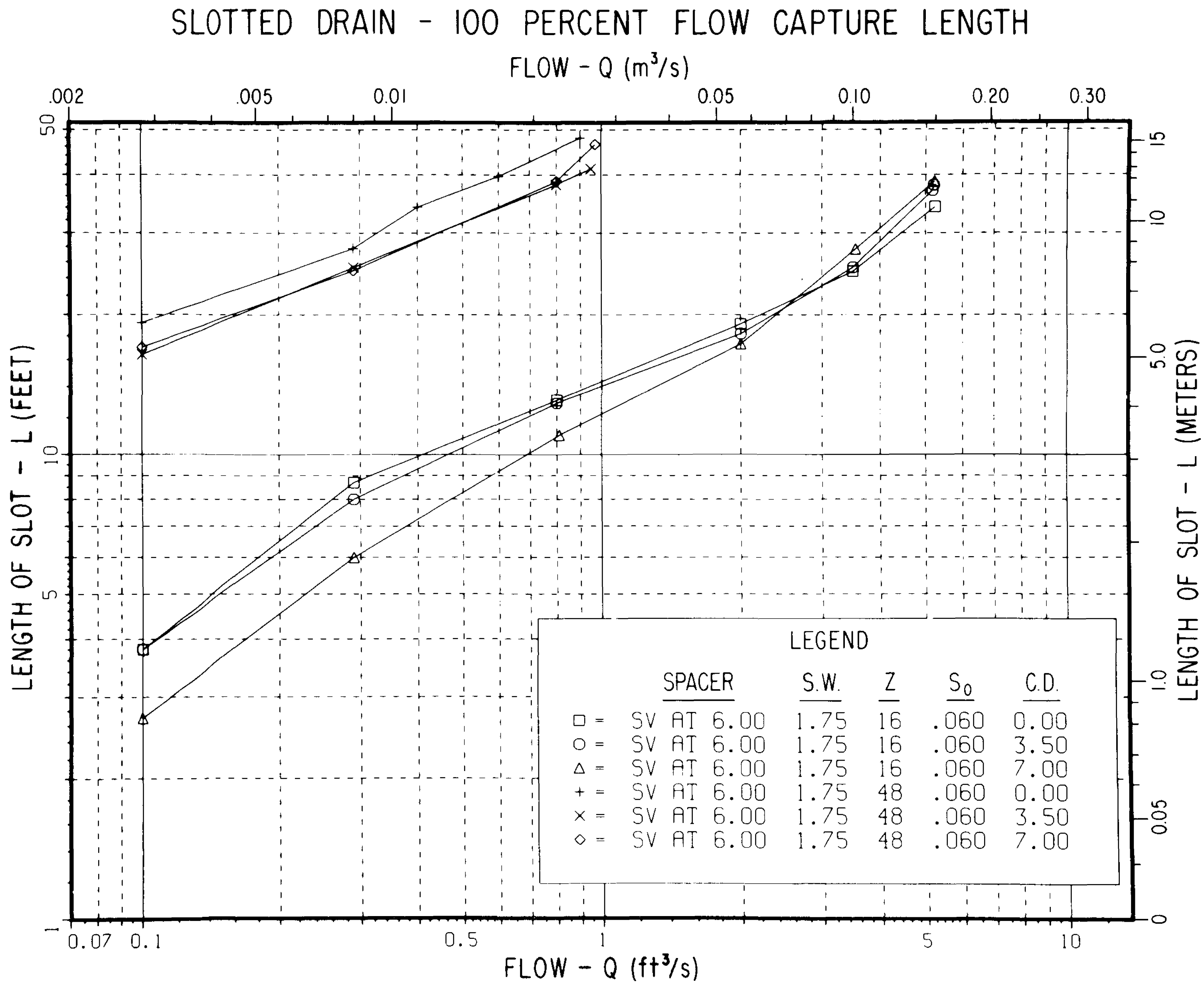


Figure 59. - Curb distance effect (log-log) Z = 16, 48; So = 0.06.

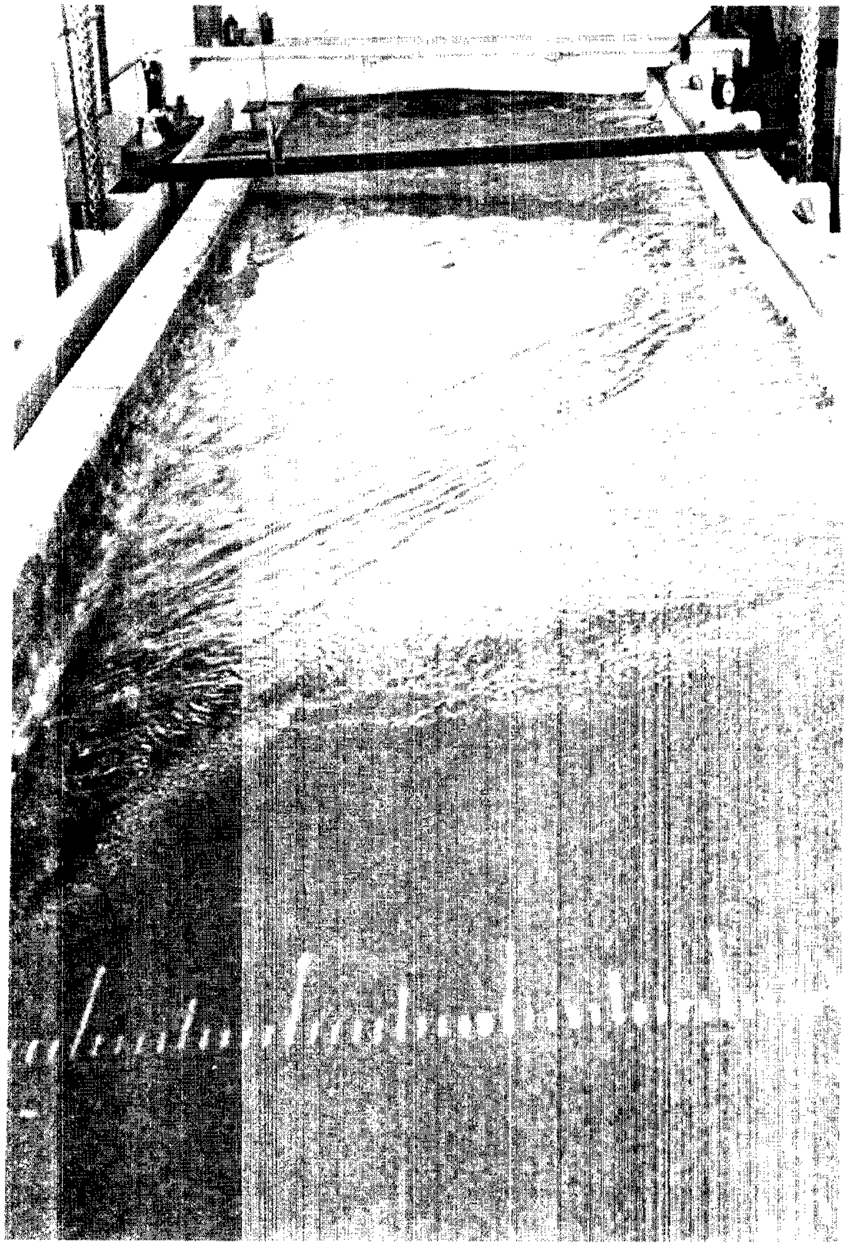


Figure 60. - Constant sheet flow added to gutter flow for combined flow tests.

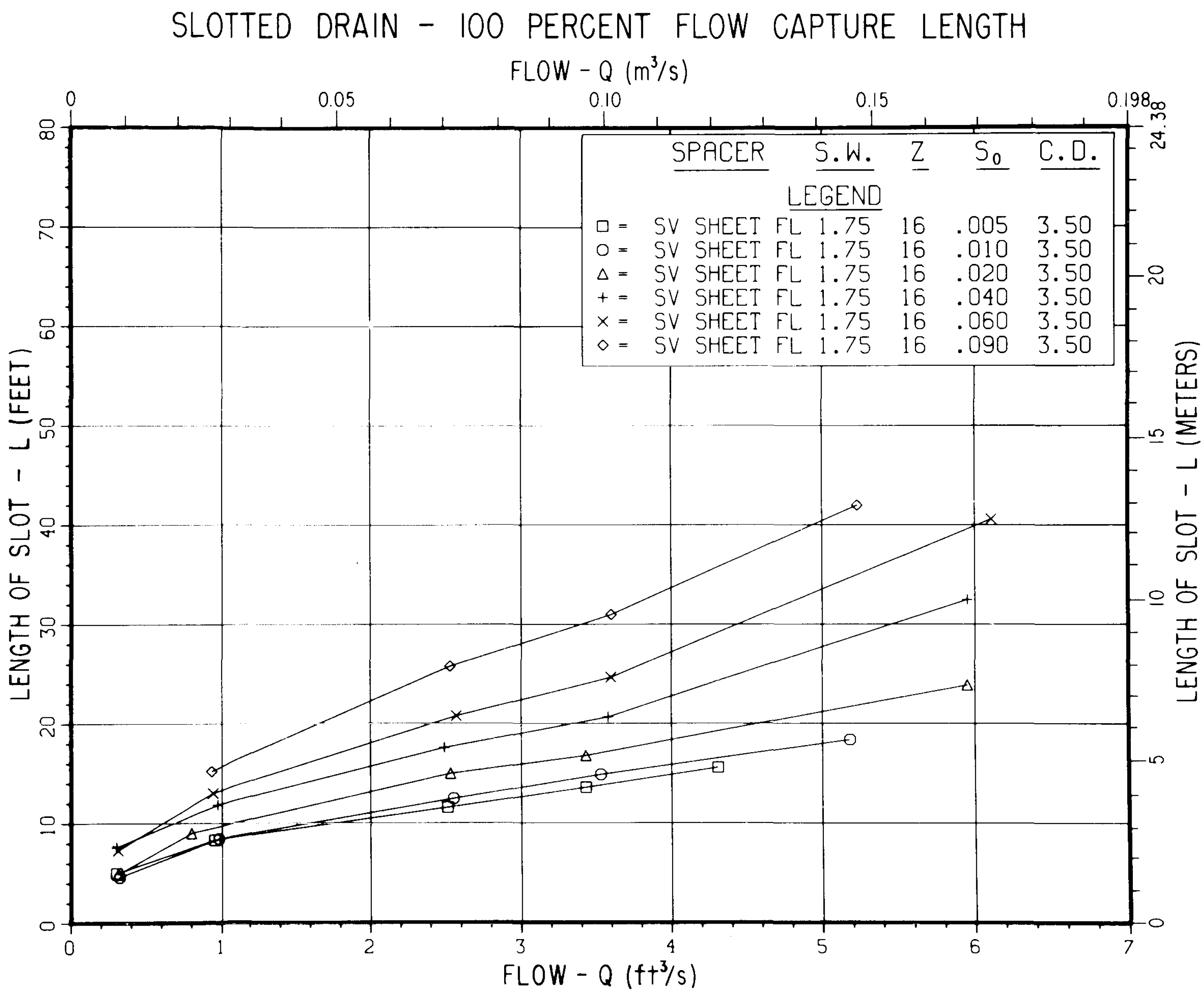


Figure 61. - Combined flow capture lengths SV(SHEET FL)-1.75-6-3.5 at Z = 16.

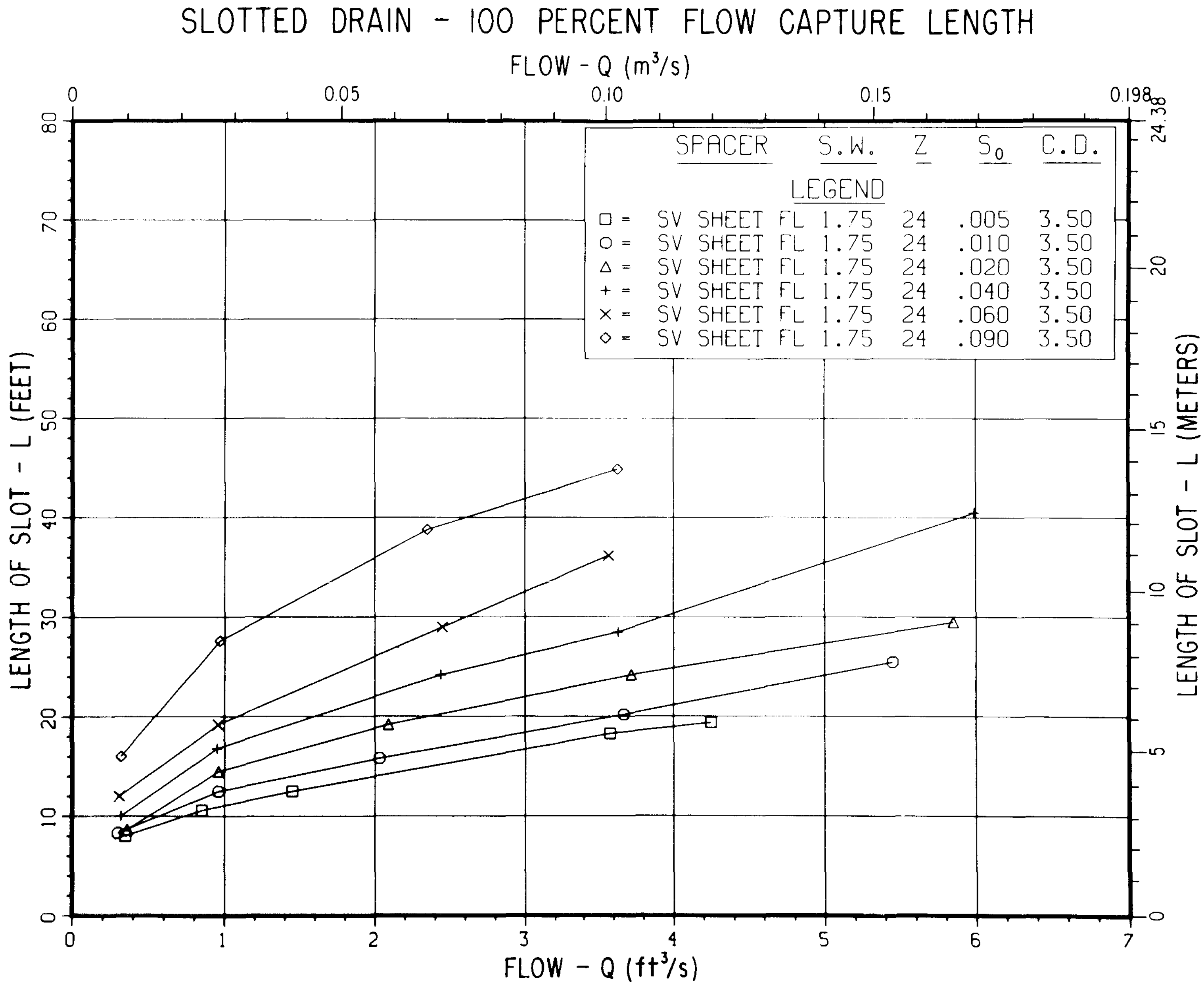


Figure 62. - Combined flow capture lengths SV(SHEET FL)-1.75-6-3.5 at Z = 24.

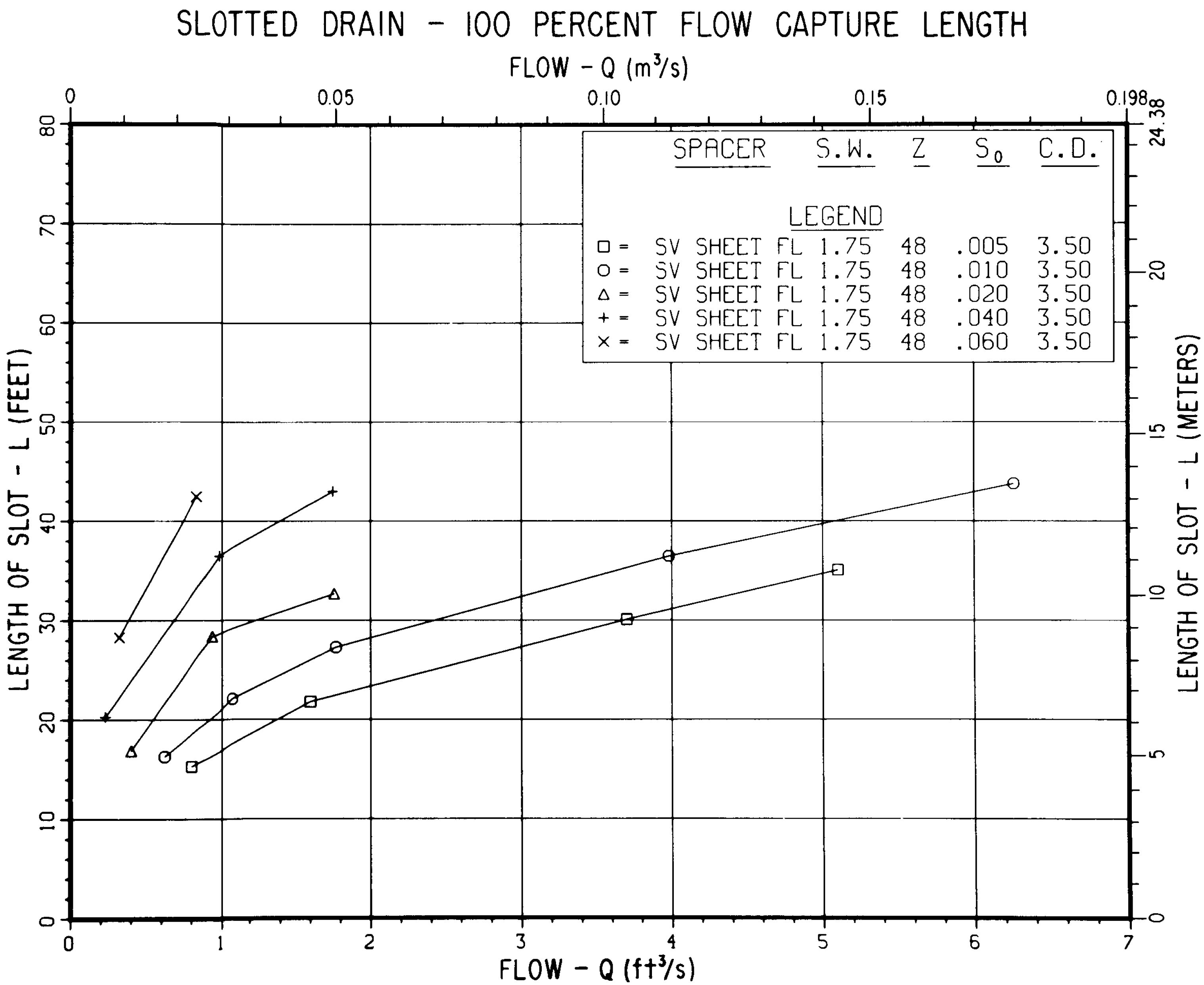


Figure 63. - Combined flow capture lengths SV(SHEET FL)-1.75-6-3.5 at Z = 48.

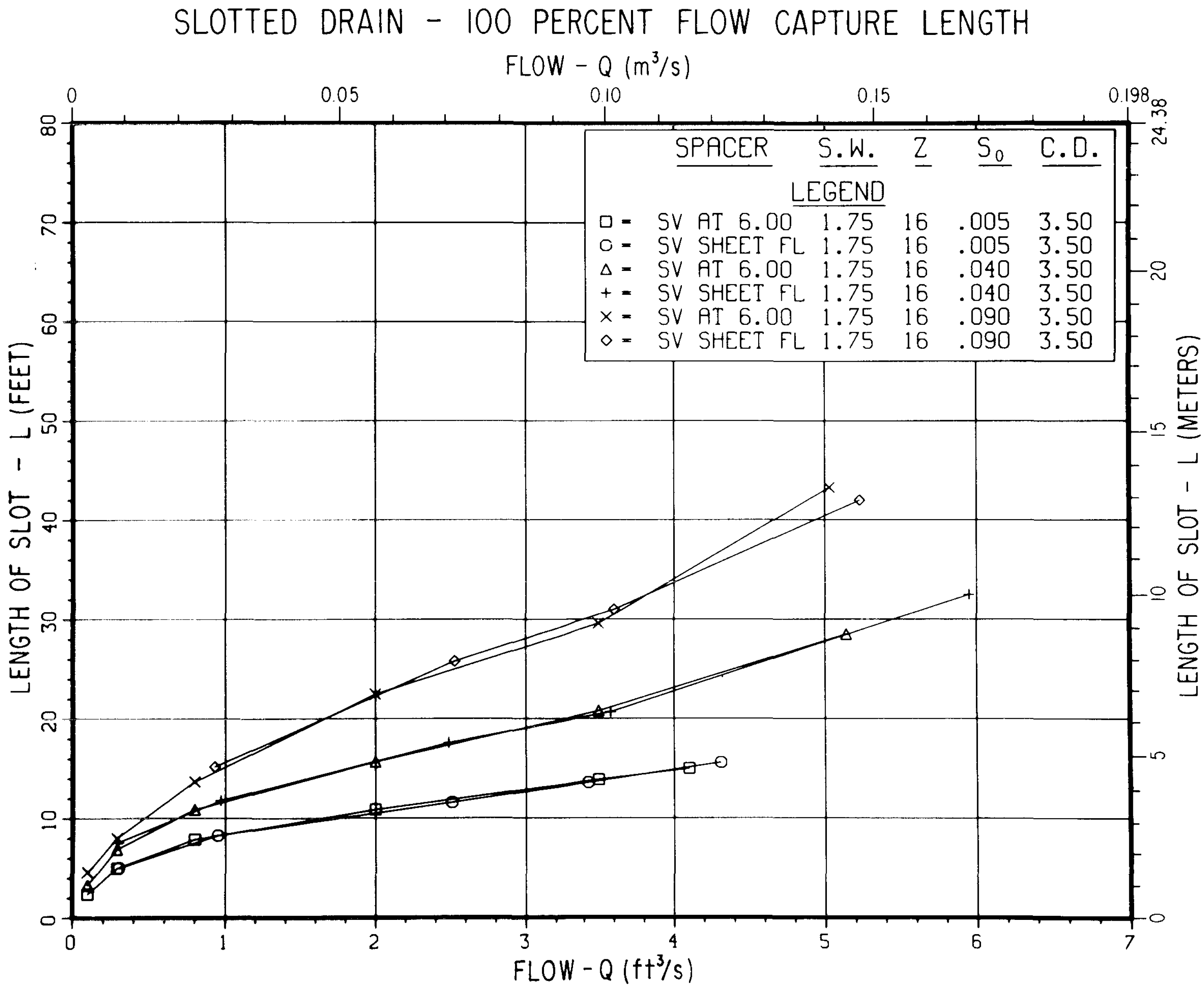


Figure 64. - Gutter flow vs. combined flow Z = 16; So = 0.005, 0.04, 0.09.

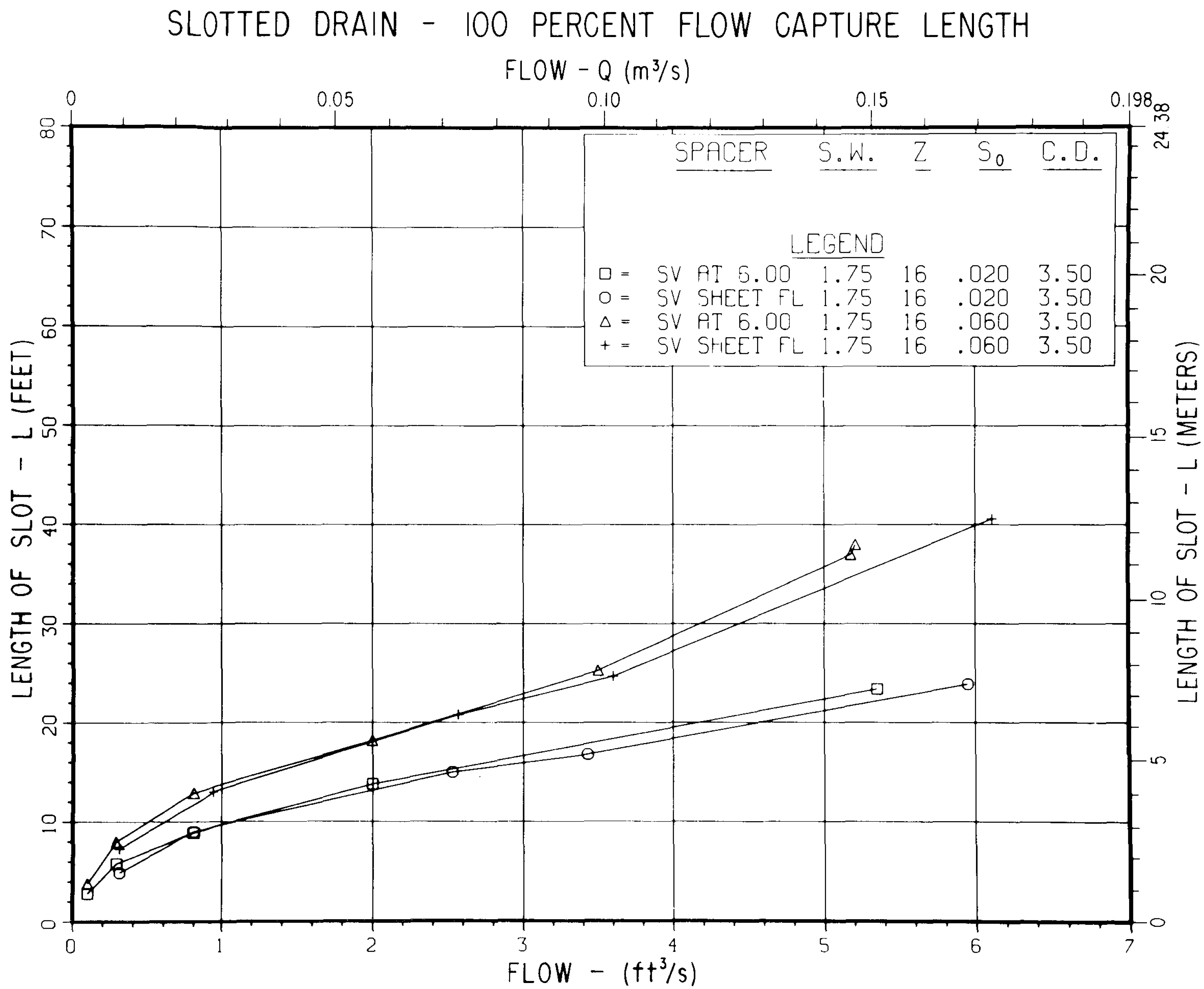


Figure 65. - Gutter flow vs. combined flow Z = 16; So = 0.02, 0.06.

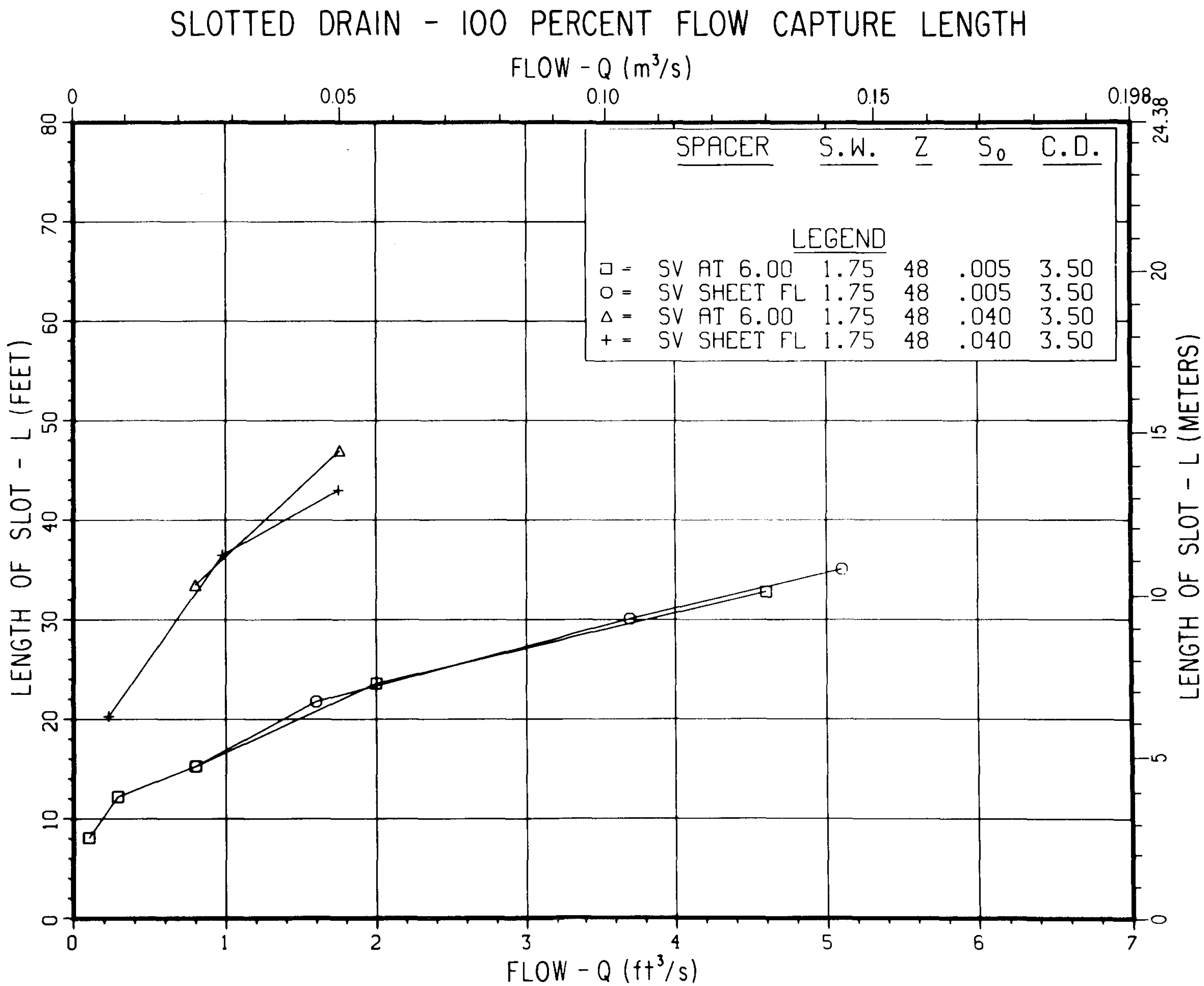


Figure 66. - Gutter flow vs. combined flow Z = 48; So = 0.005, 0.04.

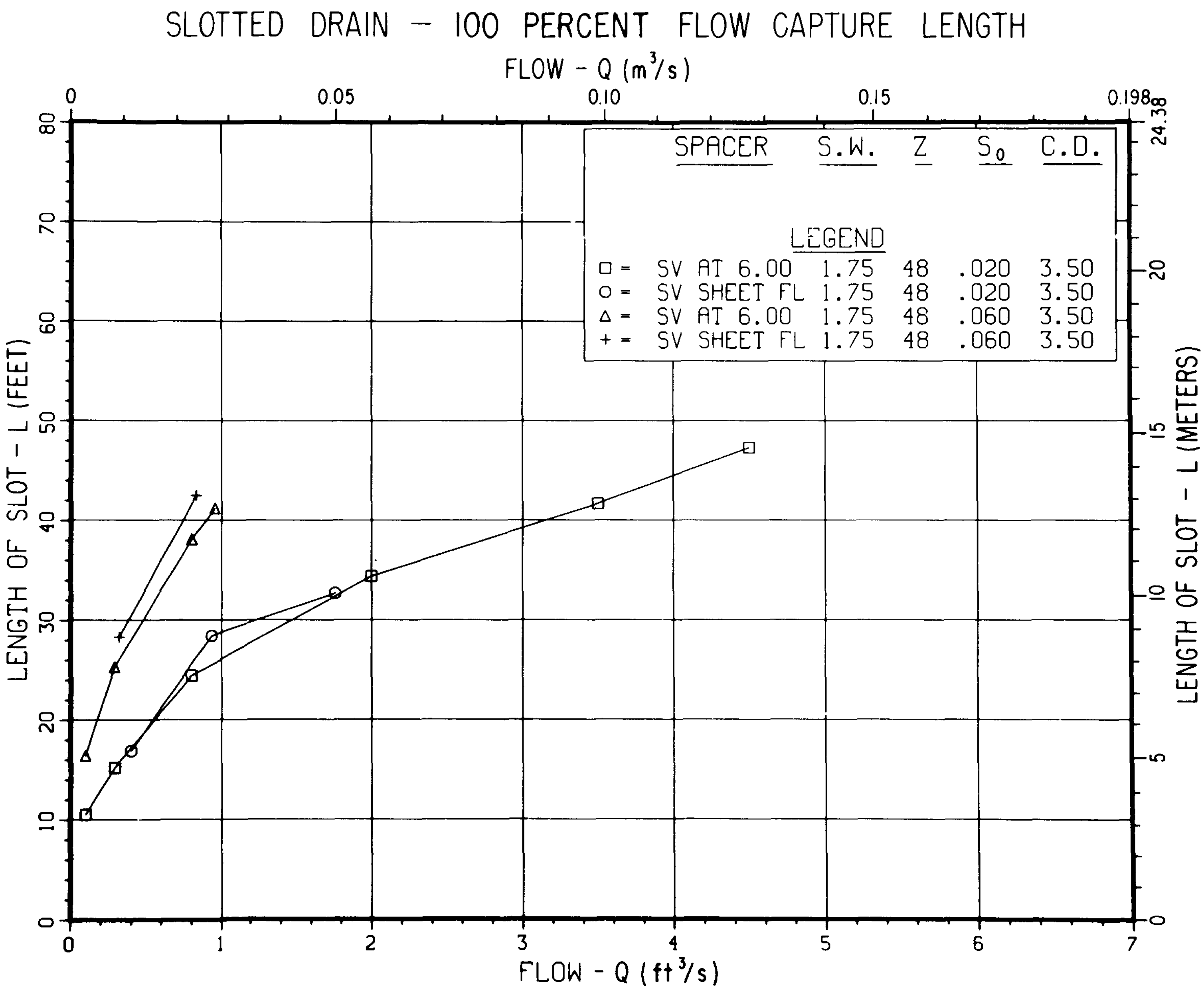


Figure 67. - Gutter flow vs. combined flow Z = 48; So = 0.02, 0.06.

Hydraulic Considerations

Flow into a slotted drain is an example of spatially varied flow with decreasing discharge. If the slot has sufficient capacity to intercept the water as weir flow, the slot acts much the same as a long curb opening inlet. Therefore, the major factor controlling the length of slot required to intercept the entire gutter flow (L) is weir flow along a triangular open channel. For a particular combination of discharge, slopes, and roadway roughness, it will take a certain length of slot to capture all of the flow regardless of the spacer type, slot width or curb distance, when weir flow is controlling.

Figure 68a depicts a situation where weir flow controls the 100 percent capture length. For a certain flow width and physical condition, the outer edge of the flow follows a predictable path. When the high velocity flow area over the upstream portion of the slot (section A-A) extends far enough downstream to overtake the outer edge of the weir flow approaching the slot (fig. 68b), weir flow no longer controls the capture length. It was observed in the model that, even in the upstream area where the slot is submerged, the roadway edge of the slot acts as a weir. The roadway flow cuts under the longitudinal flow and enters the slot as weir flow (fig. 68, section A-A). The excess flow (longitudinal flow) moves downstream and falls into the slot through the open area on the curb side. The quantity of longitudinal flow is dependent on the slot width, the type of transverse spacer, the roadway roughness, and the curb distance. As the slot becomes narrower or the spacers block the flow, more longitudinal flow builds up and moves further downstream.

Assuming weir flow in a triangular open channel, an equation can be derived for slot length (L) for total flow capture. The weir flow equation is:

$$dx = dQ/(Cw\ Y^{3/2}) \qquad (3\text{-}1)$$

where the flow depth in a trianglar channel according to Izzard (1) is:

$$Y = (nQ/0.557\ So^{1/2}\ Z)^{3/8} \qquad (3\text{-}2)$$

Y = flow depth, Q = gutter discharge, So = longitudinal slope, Z = 1/cross slope, Cw = weir flow coefficient, n = Manning's roughness coefficient, Combining equations 3-2 and 3-1:

$$dx = dQ/Cw\ (nQ/0.557\ So^{1/2}\ Z)^{9/16} \qquad (3\text{-}3)$$

intergrating over the flow interception length (L) gives:

$$L = (1.645/Cw)\ (Z\ So^{1/2}/n)^{9/16}\ Q^{7/16} \qquad (3\text{-}4)$$

If the weir coefficient is assumed to be 3.00, equation 3-4 reduces to :

$$L = 0.548\ Q^{0.438}\ So^{0.281}\ Z^{0.563}/n^{0.563} \qquad (3\text{-}5)$$

The weir flow equation assumes that the velocity through the weir is at right angles to the weir. According to Chow (2), this assumption is more satisfactory for subcritical flow than for supercritical flow. It is also assumed in the integration that the discharge decreases linearly along the slot length (L). Therefore, empirical adjustments to the coefficients in equation 3-5 are necessary.

A multiple linear regression was done to determine if a mathematical equation in the form of equation 3-5 could adequately represent the 100 percent flow capture length. Equation 3-5 was reduced to the following form for the regression.

$$L = A1\ Q^{A2}\ So^{A3}\ Z^{A4}/n^{A5} \qquad (3\text{-}6)$$

The equation was transformed to a linear form by taking the logarithms of each side. Q, So, Z, and n were assumed to be dependent variables with L being the independent variable. A1 through A5 were regression constants. One hundred ninety-five data sets were used for an SV-1.75-6-3.5 slot installation, resulting in the following regression equation:

$$L = 0.706\ Q^{0.442}\ So^{0.311}\ Z^{0.849}/n^{0.385} \qquad (3\text{-}7)$$

This equation has a standard deviation of 2.61 ft (0.796 m) at the mean. The coefficient of variability was 4.2 percent, which corresponds to one standard deviation at the mean. However, when equation 3-7 was plotted against the measured values, it was observed that errors in L were as much as 30 percent for high flows and steep slopes where weir flow does not control L. It was also noted that the exponent on So is not a constant.

The exponent (A3, hereafter referred to as A) on So in equation 3-7 was adjusted by trial and error to fit the observed data. Values of A varied from 0.21 to 0.37 and were related to So and Z. When A was graphed against So and Z, it plotted in the form of a parabola. Therefore, a regression was done relating A to So and Z in the form of a general conic.

$$A = A1 + (A2)Z + (A3)So + (A4)SoZ + (A5)So^2 + (A6)Z^2 \qquad (3\text{-}8)$$

Thirty-six sets of data were used to develop the following equation:

$$A = 0.207 + (0.007)Z + (2.610)So - (0.049)SoZ - (19.084)So^2 - (0.0001)Z^2 \qquad (3\text{-}9)$$

Table 2 gives typical values of A calculated with equation 3-9. The standard deviation in calculated vs. observed values of A was 0.01. The coefficient of variability was 4.3 percent. Equation 3-7 is then rewritten in the following form:

$$L = 0.706\ Q^{0.442}\ So^{A}\ Z^{0.849}/n^{0.385} \qquad (3\text{-}10)$$

The submerged flow condition is similar to orifice flow; however, the momentum of the longitudinal flow as well as the available slot area affect L. The slot width and transverse spacer bar affect the open area and momentum. Consequently, this flow condition cannot easily be analyzed. Another regression analysis was done using only data sets where L was not controlled by weir flow. The point where weir flow no longer controls L can be easily identified during model opertion by observing the change in flow profile (fig. 69) or by plotting L vs. Q on a log-log graph and noting the point where the slope of the line changes (see fig. 46 for an example). Thirty-four data sets were used to develop the following equation:

$$L = 0.394\ Q^{0.649}\ So^{0.410}\ Z^{0.450}/n^{0.811} \qquad (3\text{-}11)$$

The standard deviation at the mean for equation 3-11 was 2.70 ft (0.823 m) and the coefficient of variability was 2.7 percent.

The major parameter affecting L in the regression was Q. It should be noted that the exponent on Q in equation 3-10 (0.442) is very close to the exponent in the theoretical weir equation (0.438). The order of importance of the remaining variables (from the most to the least sigificant) in the regression was: Z, So, and n.

Total Flow Capture Design Method

Equations 3-10 and 3-11 both predict L closely in the ranges where they apply. Therefore, the problem of how to define the boundary between the flow regimes arises. It was found that, in the weir flow zone, equation 3-10 for weir flow predicts a larger value for L than equation 3-11. In the area where weir flow does not control, equation 3-11 predicts a larger value. Therefore, it is suggested that L be computed using both equations 3-10 and 3-11 and the larger of the two values be used to determine the design value for L.

When this method was used to compare observed and computed values of L, the correlation was very good (see fig. 70 through 75). The transition point between the two flow regimes matched observations closely for both roughness values (n = 0.009 and 0.0165). The standard deviation at the mean between observed and computed values of L was 1.66 ft (0.51 m), and the coefficient of variability was 2.8 percent.

The data used for this analysis were in the range from Q = 0.3 to 6.0 ft^3/s (0.008 to 0.17 m^3/s) and from L = 4 to 48 ft (1.2 to 14.6 m). Values predicted using equations 3-10 and 3-11 which are out of the range of the data should be used with caution since they have not been experimentally verified.

It should also be noted that the above analysis is for a 1.75-in (44.45-mm) wide slot with solid transverse bars at 6-in (152.4-mm) spacing. However, the weir flow equation (3-10) for 100 percent flow capture still applies to other slot widths and spacer designs. Equation 3-11 applies only to SV-1.75-6-3.5 slot installations in the submerged flow range. A design method accounting for slot width and curb distance will be covered in volume 5.

Weir flow controls L for all conditions tested on the double bar spacers and the 2-1/2-in (63.5-mm) wide slot. At Z = 24 and n = 0.0165 weir flow controls L for all conditions tested, except where a 1.00-in (25.4-mm) slot width was used. At Z = 48, weir flow controls L for all conditions tested. Most field conditions encountered will fall into the weir region for 100 percent capture and equation 3-10 will apply.

This analysis is for total flow capture only. If the efficiency of each incremental section of slot were analyzed, the wider slots and slots with transverse spacers not obstrucing the flow as much (i.e., double bar and 45° angle spacers) would be expected to have higher efficiencies in the upstream portion even though the 100 percent capture length would be the same in the weir flow region.

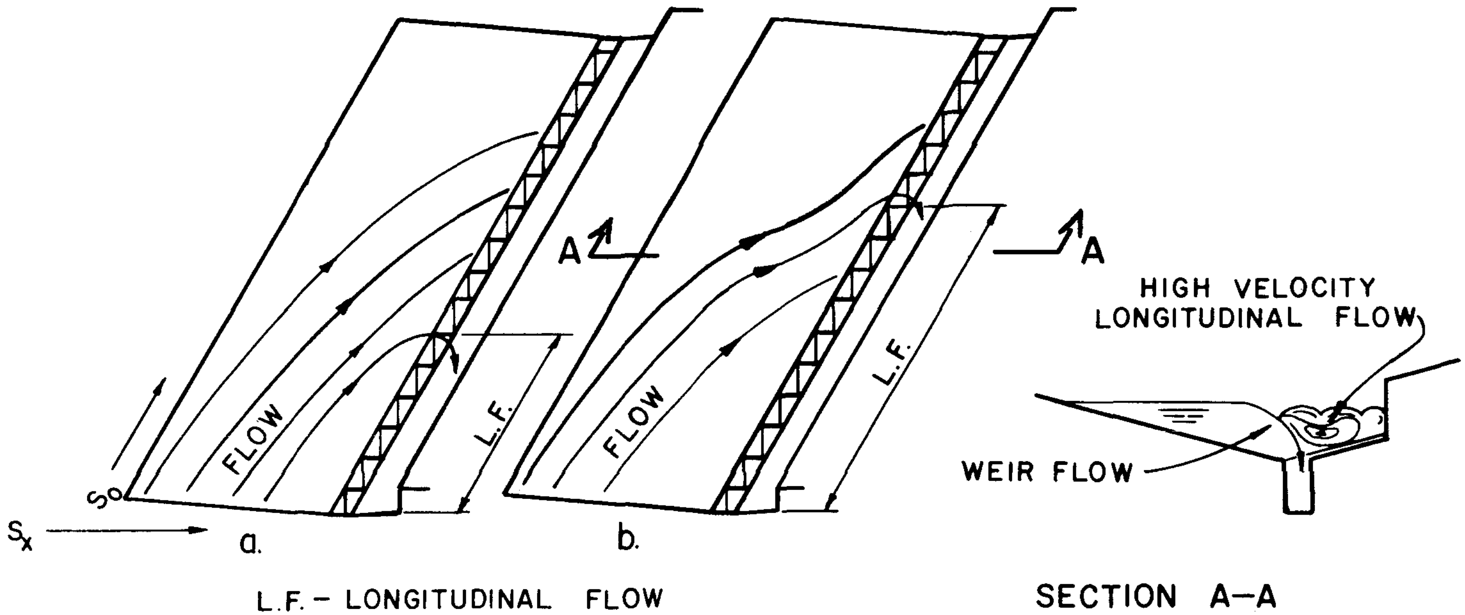
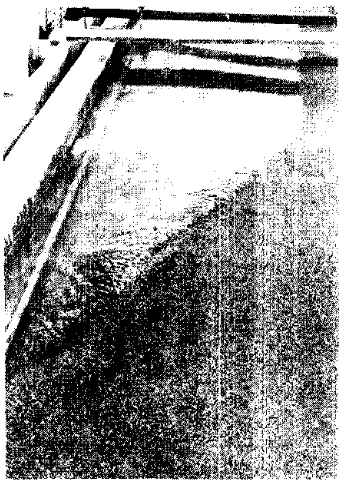


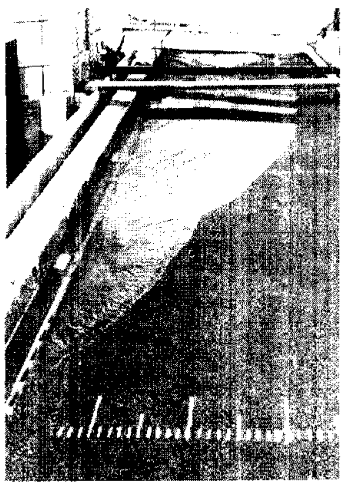
Figure 68. - 100 percent capture - flow conditions.

Table 2. - Values of A calculated with Equation 3-9 for use in Equation 3-10

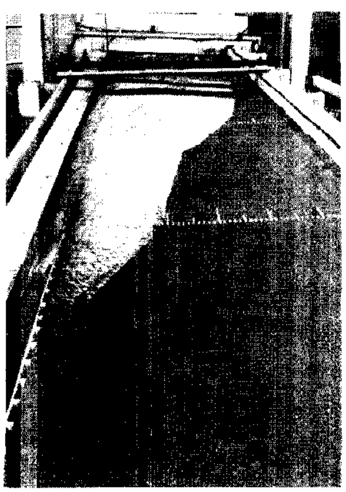
So	Z 16	20	24	28	32	36	40	44	48
0.005	0.302	0.315	0.324	0.330	0.333	0.333	0.330	0.323	0.313
0.010	0.310	0.321	0.330	0.335	0.337	0.336	0.332	0.324	0.313
0.015	0.317	0.327	0.335	0.339	0.340	0.338	0.333	0.324	0.312
0.020	0.322	0.332	0.339	0.342	0.342	0.339	0.332	0.323	0.310
0.025	0.327	0.336	0.341	0.344	0.343	0.339	0.331	0.321	0.307
0.030	0.331	0.339	0.343	0.345	0.343	0.338	0.329	0.318	0.303
0.035	0.334	0.341	0.344	0.345	0.342	0.336	0.326	0.314	0.298
0.040	0.336	0.342	0.344	0.344	0.340	0.333	0.323	0.309	0.293
0.045	0.337	0.342	0.343	0.342	0.337	0.329	0.318	0.303	0.286
0.050	0.337	0.341	0.346	0.339	0.333	0.324	0.312	0.297	0.278
0.055	0.336	0.339	0.339	0.335	0.328	0.318	0.305	0.289	0.269
0.060	0.334	0.336	0.335	0.330	0.323	0.312	0.297	0.280	0.260
0.065	0.332	0.333	0.331	0.325	0.316	0.304	0.289	0.270	0.249
0.070	0.328	0.328	0.324	0.318	0.308	0.295	0.279	0.260	0.237
0.075	0.323	0.322	0.318	0.310	0.300	0.286	0.269	0.248	0.225
0.080	0.318	0.316	0.310	0.302	0.290	0.275	0.257	0.236	0.211
0.085	0.311	0.308	0.302	0.292	0.280	0.264	0.245	0.222	0.197
0.090	0.303	0.299	0.292	0.282	0.268	0.251	0.231	0.208	0.182



a. Q = 2.3 ft^3/s (0.065 m^3/s) weir flow controlling L.



b. Q = 2.7 ft^3/s (0.076 m^3/s) submerged flow controlling L.



c. Q = 3.5 ft^3/s (0.099 m^3/s) note the elongated shape of the downstream flow area.

Figure 69. - Change in flow profile during 100 percent capture tests. Slot width = 1.00 in (25.4 mm), So = 0.02, Z = 16. (Also see figs. 46 and 68.)

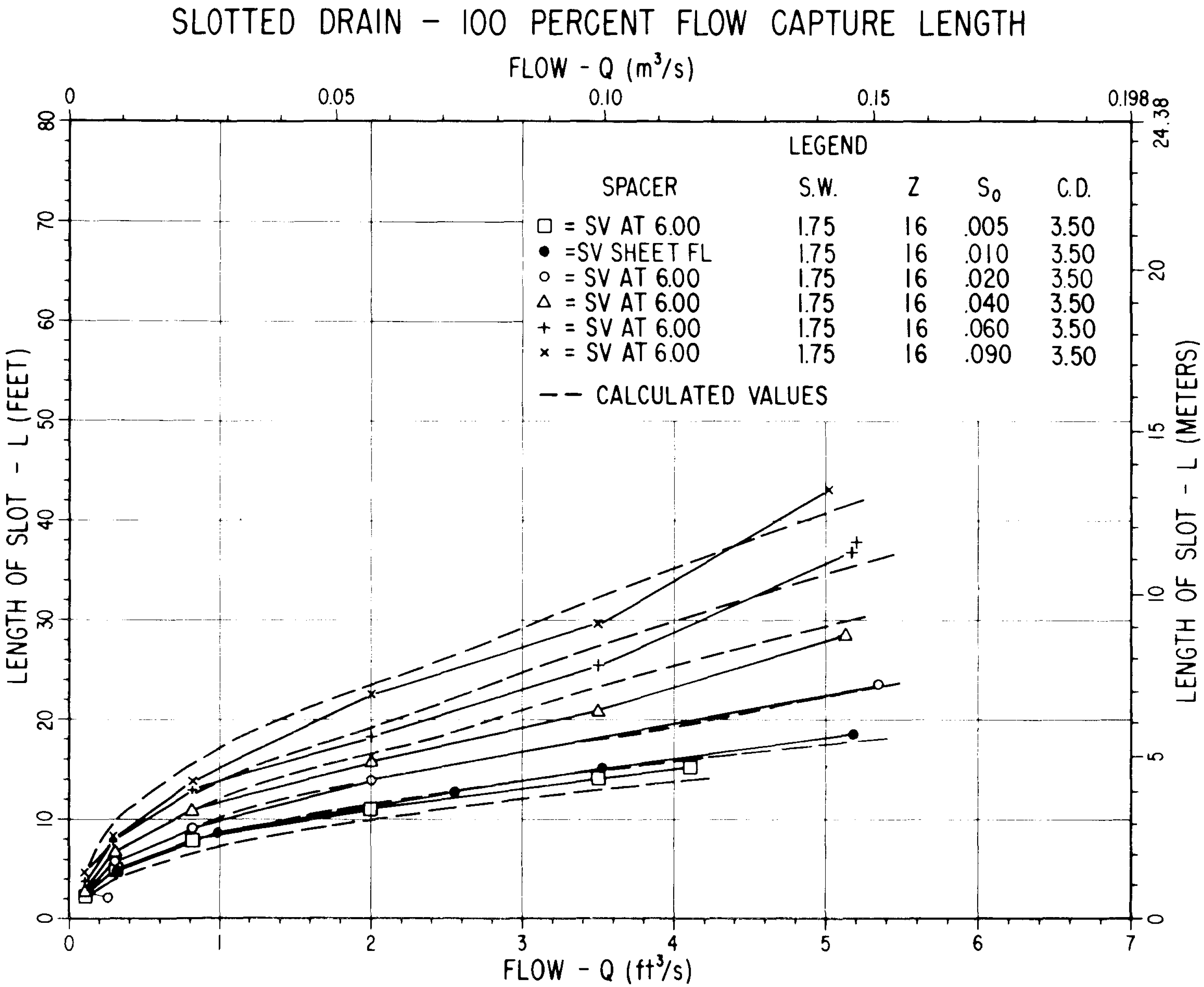


Figure 70. - 100 percent flow capture length - observed vs. calculated SV-1.75-6-3.5 at Z = 16.

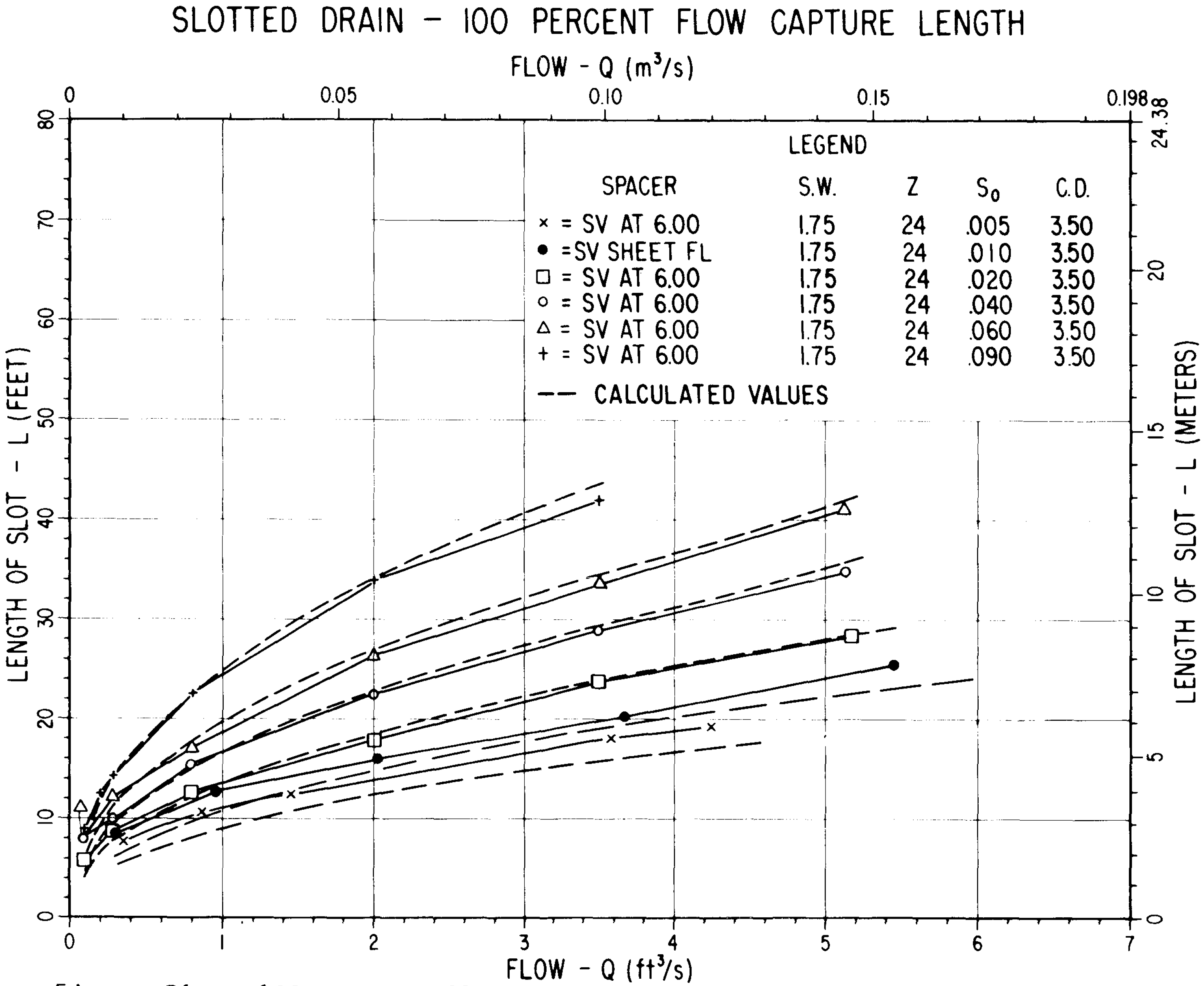


Figure 71. - 100 percent flow capture length - observed vs. calculated SV-1.75-6-3.5 at Z = 24.

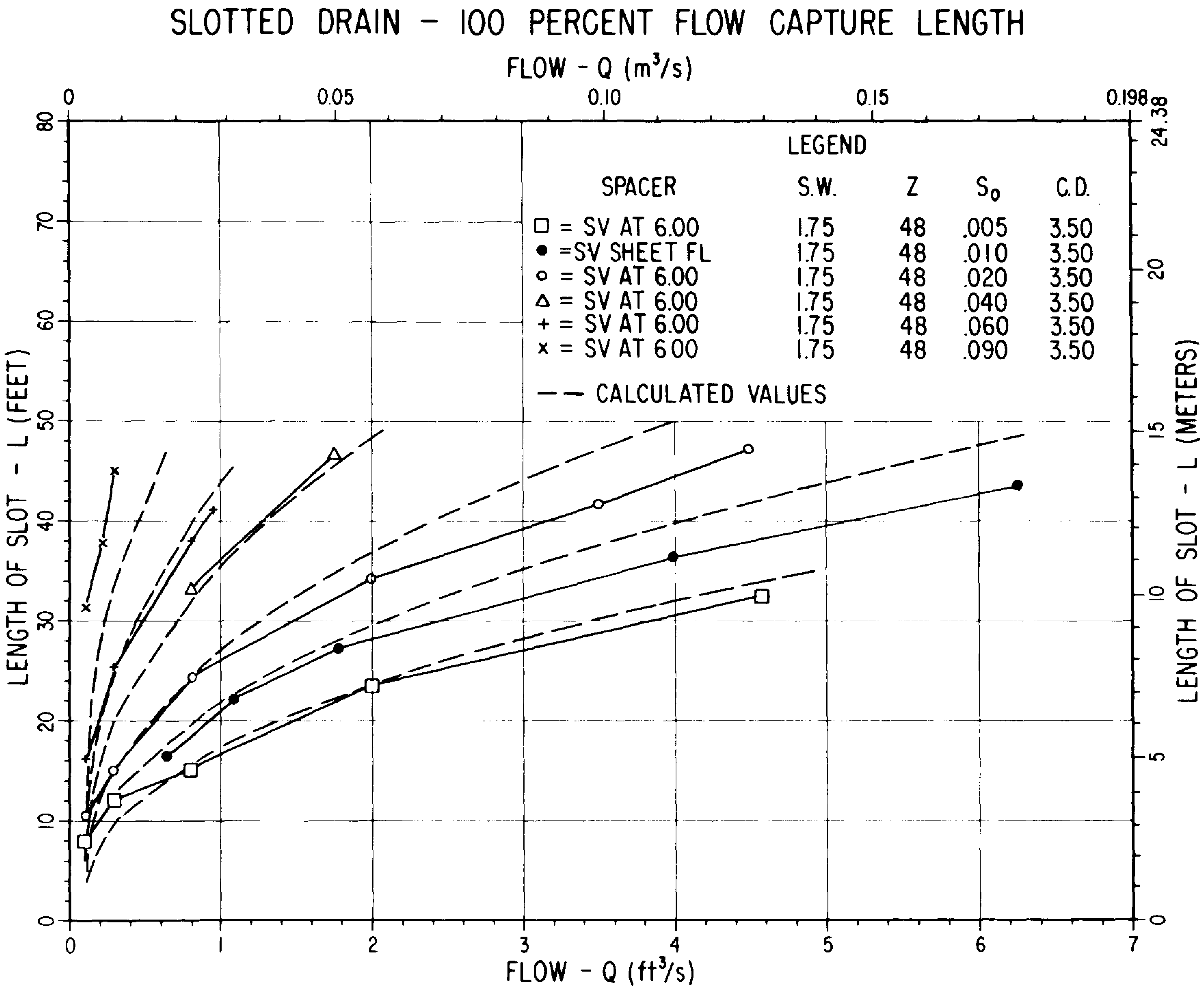


Figure 72. - 100 percent flow capture length - observed vs. calculated SV-1.75-6-3.5 at Z = 48.

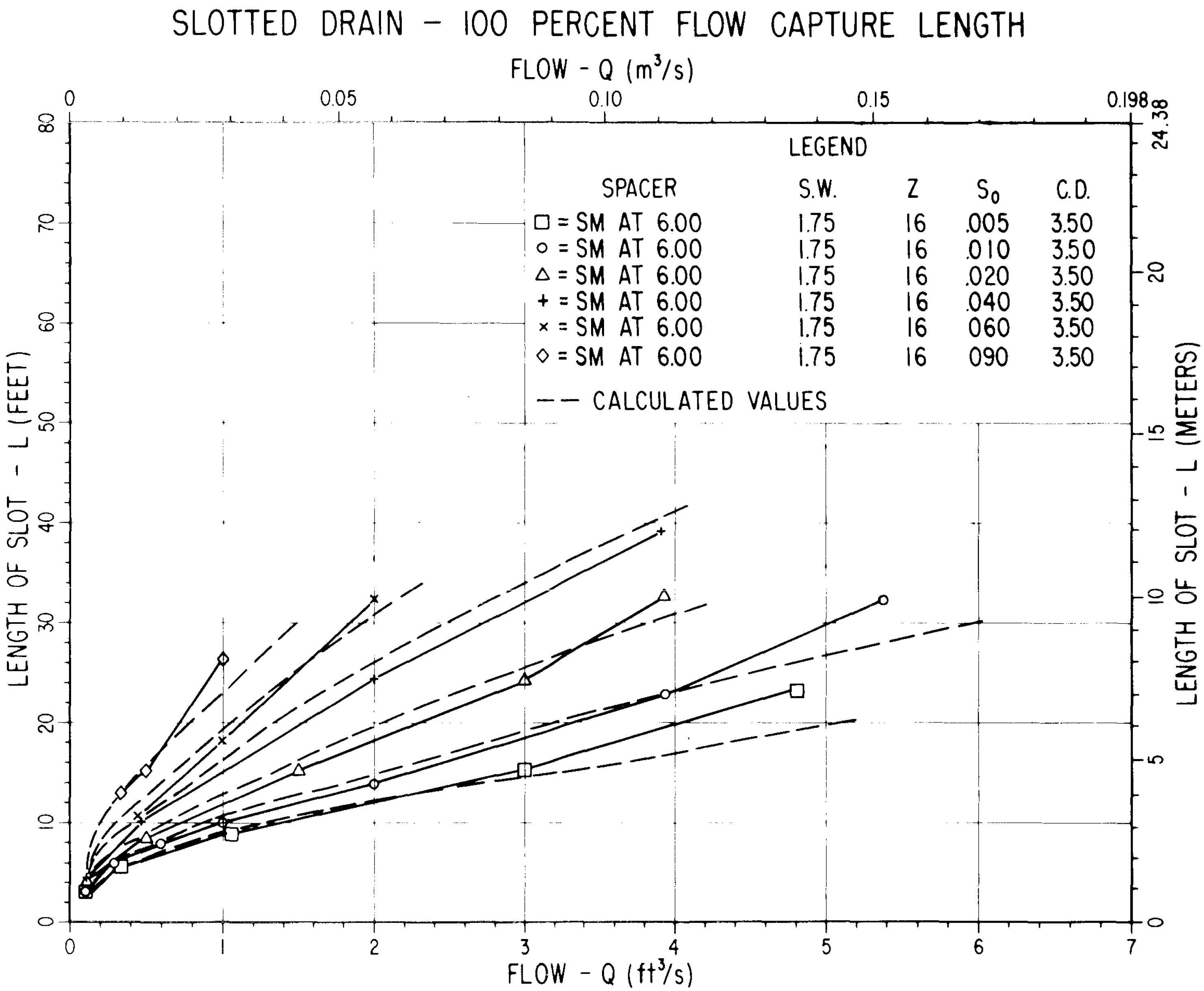


Figure 73. - 100 percent flow capture length - observed vs. calculated SM-1.75-6-3.5 at Z = 16.

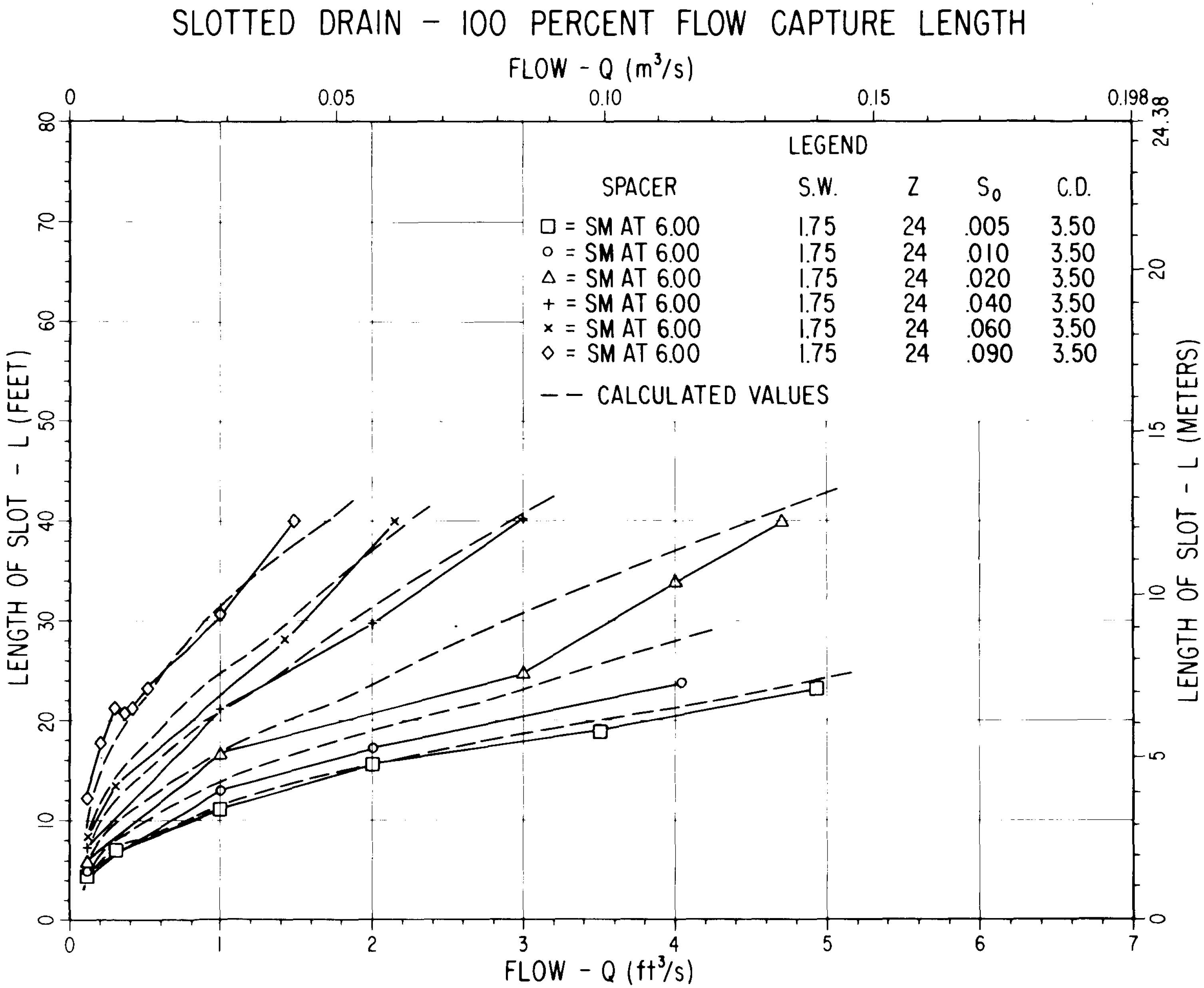


Figure 74. - 100 percent flow capture length - observed vs. calculated SM-1.75-6-3.5 at Z = 24.

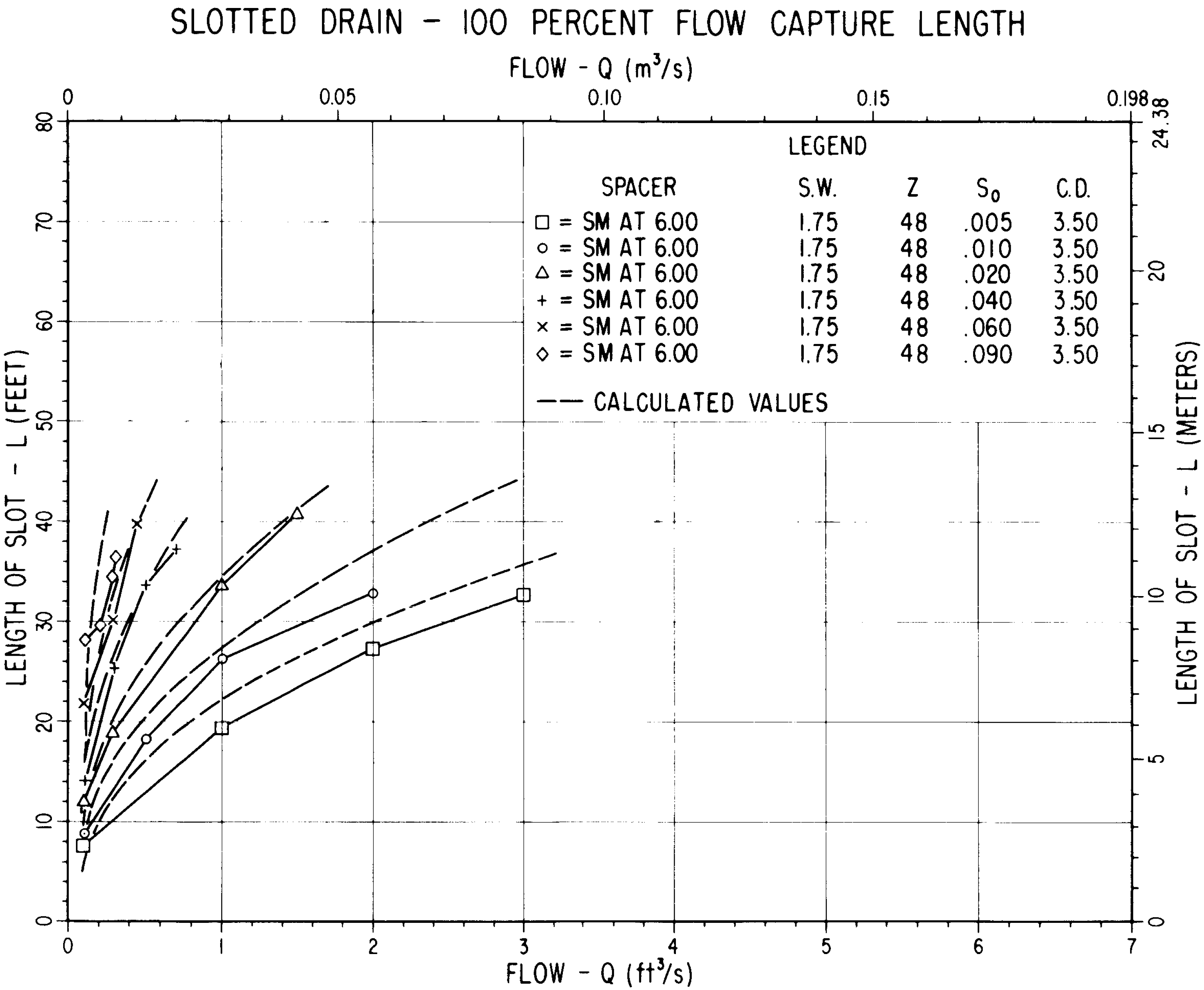


Figure 75. - 100 percent flow capture length - observed vs. calculated SM-1.75-6-3.5 at Z = 48.

Comparison with Previous Study

The test conditions for a smooth roadway surface compare closely with tests conducted by Masch (3). Masch also used a painted plywood roadway surface. There was, however, a difference between the measured n values. Masch determined n to be between 0.011 and 0.012, while the n value for the Bureau of Reclamation tests was determined to be 0.009. The discrepancy could be due to the difference in the methods used to determine n. Masch used a triangular cross section and measured several depths along the 60 ft (18.3 m) of roadway, while the Bureau of Reclamation used a rectangular cross section and measured depths at 3-in (76.2-mm) intervals across the roadway, 35 ft (11 m) downstream from the headbox. The distance from the curb face to the slot was slightly different between the two studies. In Masch's tests, the curb face was 3.50-in (88.9-mm) from the slot centerline. In the Bureau of Reclamation study, the curb was 3.50 in (88.9 mm) from the edge of the slot. However, the difference is only 0.88 in (22.2 mm). The effect of this difference is probably negligible. In the tests done by the Bureau of Reclamation, the effect of a 3.50-in (88.9-mm) difference in curb distance was evident only in steep slope conditions and even then it was small (see fig. 57 through 59).

Figures 76 through 78 compare Bureau of Reclamation results with Masch's results for an SM-1.75-6-3.5 slot installation. For longitudinal slopes of 1, 2, and 4 percent. At higher discharges, the Bureau of Reclamation data agreed closely with Masch's data. At lower discharges, Bureau of Reclamation data continue to follow the slope of a weir equation (7/16). The slope of Masch's data decreases as the discharge decreases.

Masch pointed out that according to the theoretical weir equation (3-5), a rougher roadway surface would reduce L by the ratio $(n\text{-smooth}/n\text{-rough})^{0.563}$. The Bureau of Reclamation data indicate that a rougher roadway would decrease L by the ratio $(n\text{-smooth}/n\text{-rough})^{0.385}$ in the weir flow region and for submerged flow $(n\text{-smooth}/n\text{-rough})^{0.811}$.

Debris Tests

The results of the debris tests are given in table 3. Figures 79, 80, and 81 are photographs of typical debris tests. At flat cross slopes and steep longitudinal slopes, the double bar spacer is less efficient than the other spacer designs. This is because more of the debris tends to wrap around the bars when the flow is mainly longitudinal.

The most important variable affecting debris handling capability is the transverse bar spacing. When the spacing was changed from 6 in (152.4 mm) to 4 in (101.6 mm), the debris efficiency dropped by one-half for the double bar and by one-third for the solid vertical bars, on the average.

Curb distance has a slight effect on debris efficiency. Generally, the condition with the curb adjacent with the slot was the most efficient.

Slot width has the expected effect on debris efficiency. The wider slots with more open area are more efficient. There is about a 20 percent improvement in efficiency between a 1.00-in (25.4-mm) wide slot and a 2.50-in (63.5-mm) wide slot.

References

[1] Izzard, C. F., "Hydraulics of Runoff from Developed Surfaces," Highway Research Board, Volume 26, 1946

[2] Chow, V. T., Open Channel Hydraulics, McGraw-Hill Book Company, Inc., New York, 1959

[3] Masch, F. D., "Limited Capacity Studies on Armco Slotted Drain Pie," Report to Armco Steel Corporation, January 1978

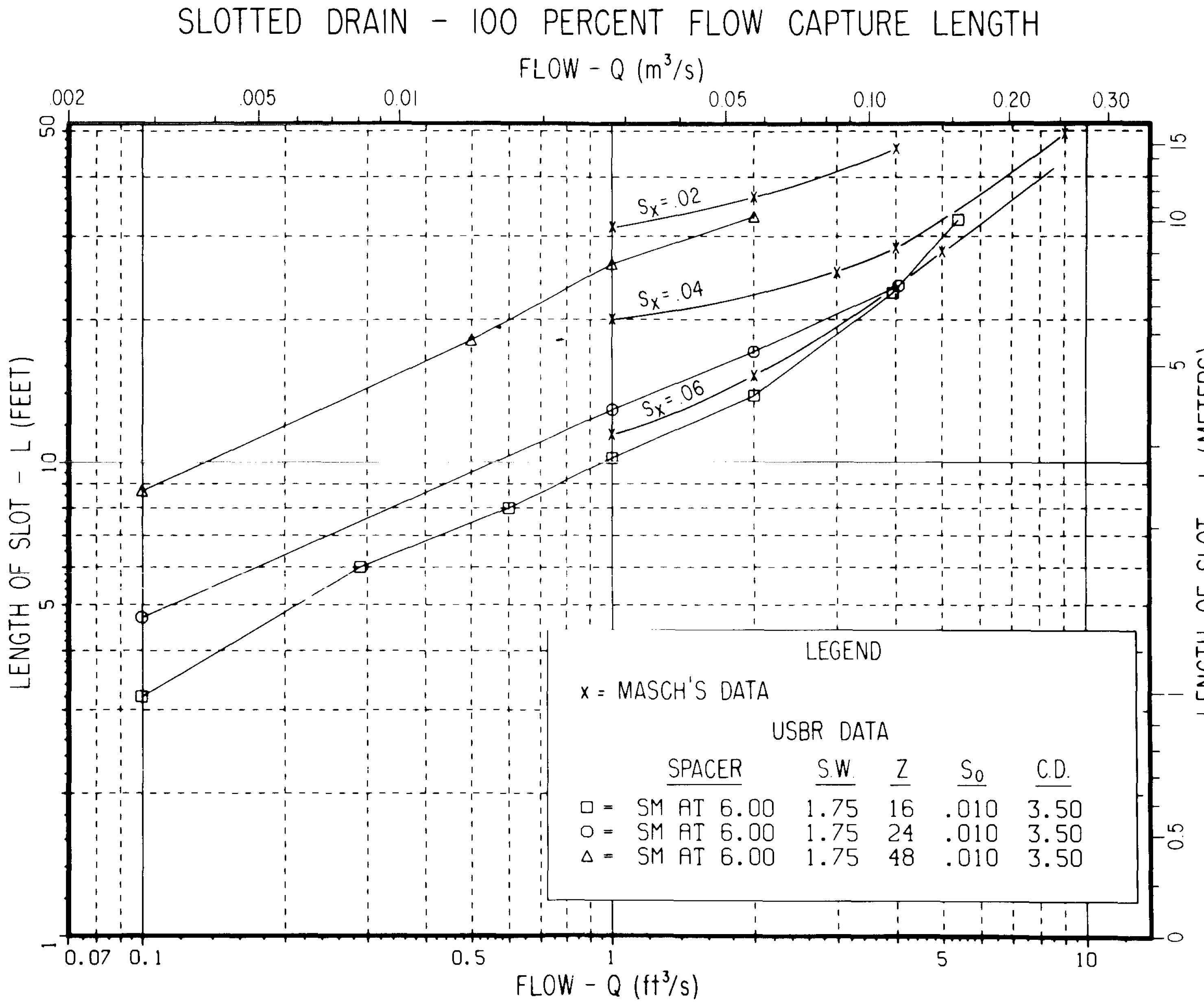


Figure 76. - Comparison with previous study, So = 0.01.

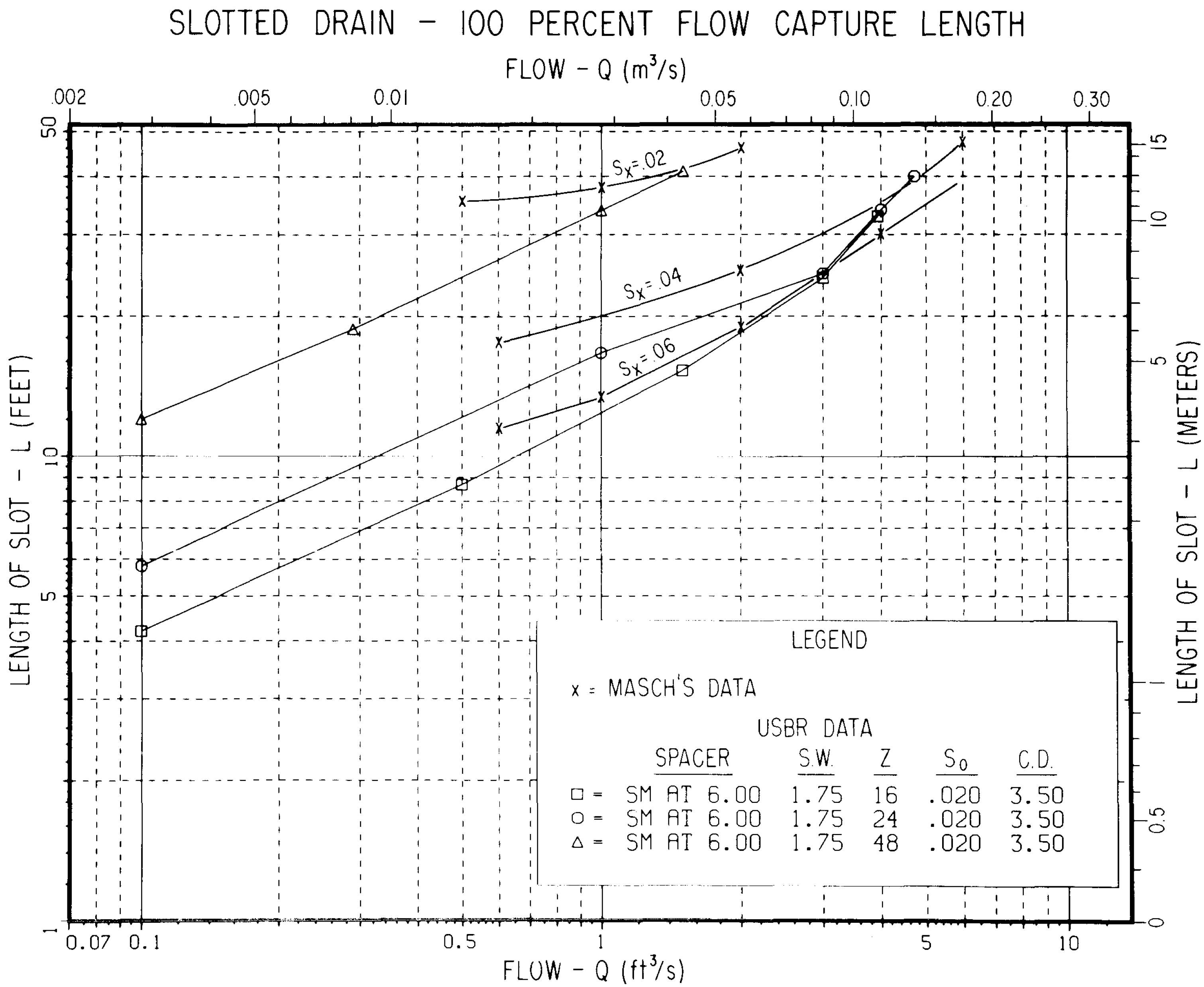


Figure 77. - Comparison with previous study, So = 0.02.

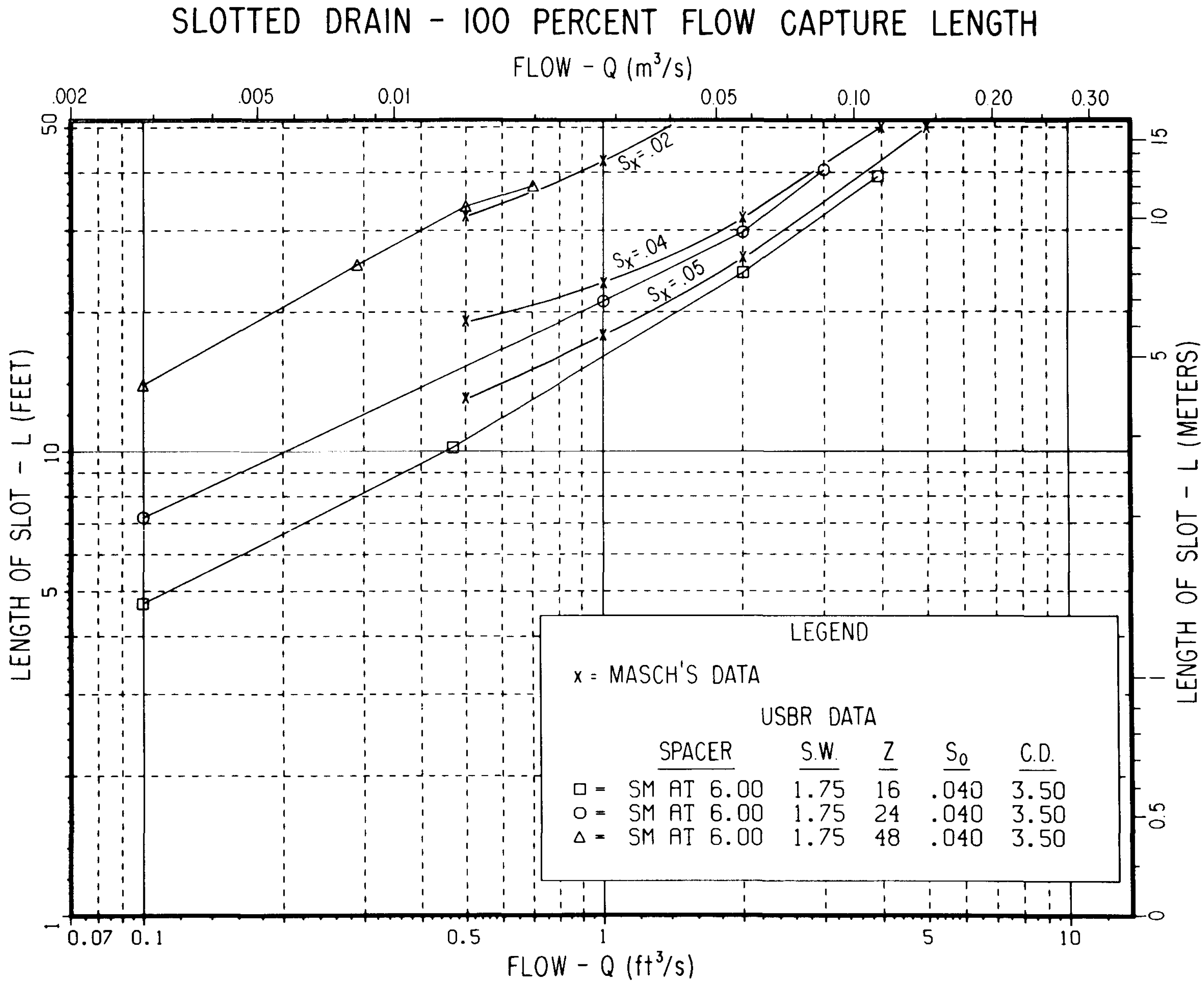


Figure 78. - Comparison with previous study, So = 0.04.

Table 3. - Average debris efficiency $\bar{E}$ * (percent) for slotted drain

	Longitudinal slope = 0.04									Longitudinal slope = 0.005								
Curb ** distance	0	7	3.50														0	7
Spacer type	Solid vertical				45°	Double bar		Solid vertical				Double bar		45°	Solid vertical			
Spacer ** spacing	6			4	6	4	6						4	6	4	6		
Slot ** width	1.75							1.00	2.50	1.00	2.50	1.75						
S_x = 1/16	86	82	80	46	78	43	76	60	85	70	88	80	49	79	66	77	78	73
S_x = 1/48	68	54	63	25	52	18	37	53	73	63	73	74	29	68	57	64	72	63

* Debris efficiency is the percentage of 150, 3- by 4-inch pieces of debris passing through the slot. Each value is the average of three tests.
** The curb distance, spacer spacing, and slot width are given in inches (1 inch = 25.4 mm).

Figure 79. - View looking downstream of debris test, 1.75-in (44.45-mm) wide slot with vertical spacers at 6-in (152.4-mm) spacing. Curb distance = 0 in, So = 0.04, Z = 16, $\overline{E}$ = 86 percent.

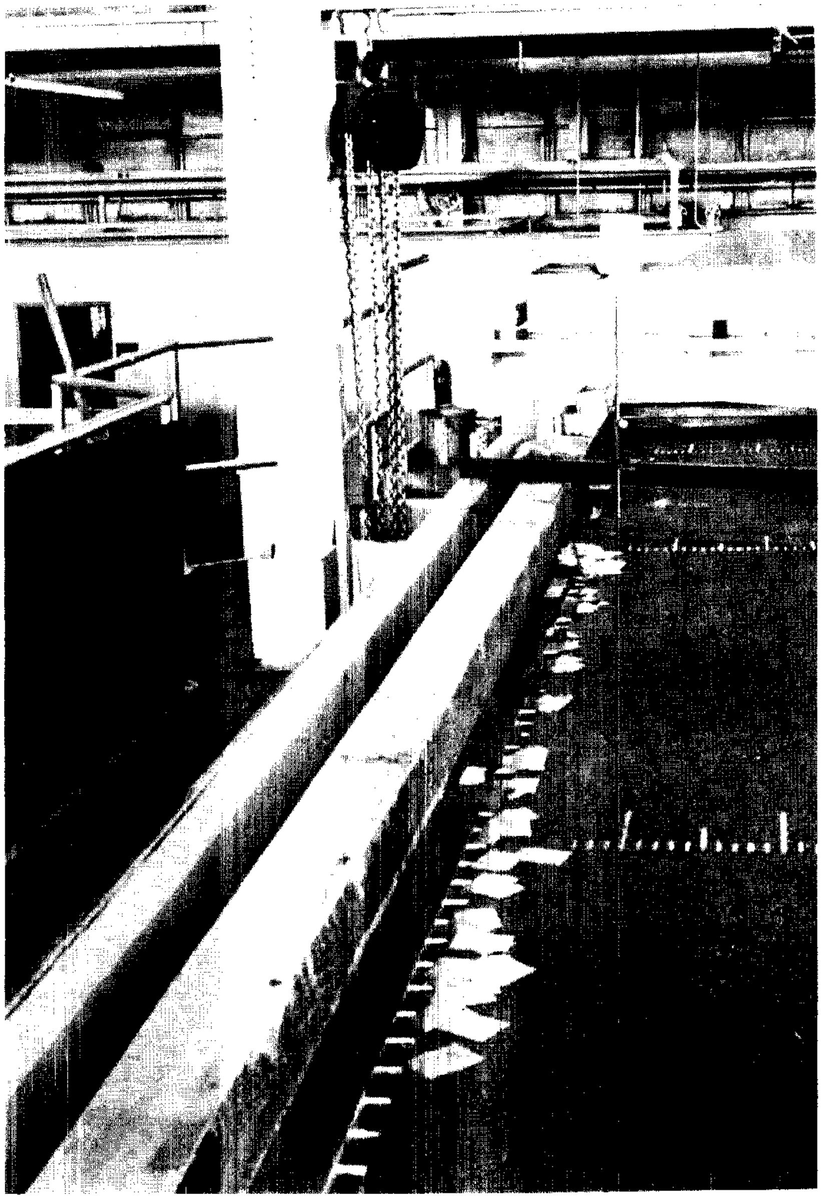


Figure 80. - View looking upstream of debris test, 1.75-in (44.45-mm) wide slot with double bar spacers at 4-in (101.6-mm) spacing. Curb distance = 3.50 in (88.9 mm), So = 0.005, Z = 48, $\overline{E}$ = 29 percent.

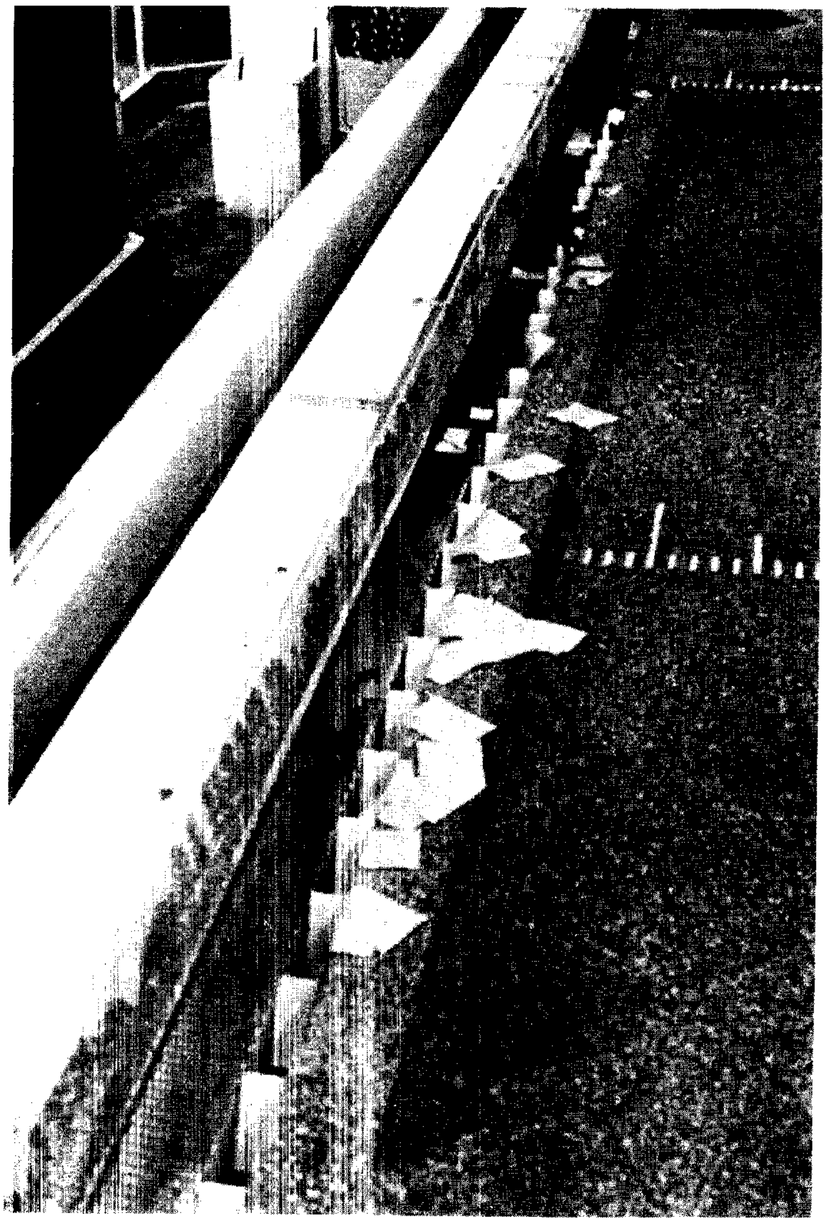


Figure 81. - View looking upstream of debris test, 1.75-in (44.45-mm) wide slot with solid spacers at a 45 degree angle at 6-in (152.4-mm) spacing. Curb distance = 3.50 in (88.9 mm), So = 0.005, Z = 48, $\overline{E}$ = 68 percent.

CHAPTER 4

SHEET FLOW TESTS

Sheet or overland flow was tested for unit discharges "q" up to 0.040 ft^3/s per ft (0.345 L/s per m). The test procedure was to establish a uniform sheet flow and measure the amount of flow passing over the slot. Slots with solid vertical spacers at 6-in (152.4-mm) spacing were used. Slot widths of 1.00, 1.75, and 2.50 in (25.4, 44.45, and 63.5 mm) were tested. Care was taken to ensure that flow did not go around the ends of the slot. Figure 82 is a photograph of a sheet flow test.

The sheet flow supply system is described in Chapter 2. The system was designed to supply at least 0.025 ft^3/s per ft (0.216 L/s per m). The actual system capacity was 0.040 ft^3/s per ft (0.345 L/s per m). A unit discharge of 0.025 ft^3/s per ft (0.216 L/s per m) corresponds to a rainstorm of 15.0 in/h (343 mm/h) over a 72-ft (21.9-m) wide roadway (6 lanes). The Manning's n value for the sheet flow tests was 0.0165.

At the maximum unit discharge q = 0.040 ft^3/s per ft (0.345 L/s per m), the water ranged in depth from 0.38 in (9.7 mm) at So = 0.09 and Z = 16; to 0.56 in (14.2 mm) at So = 0.005 and Z = 48. This corresponds to a velocity range of 0.857 to 1.263 ft/s (0.330 to 0.385 m/s) between the maximum and minimum slopes. For flows this shallow, boundary shear holds the velocity fairly constant over a range of slopes.

Results

All three slot widths accepted nearly all the sheet flow up to the system capacity, q = 0.040 ft^3/s per ft (0.345 L/s per m). The only overflow was a small amount of splash from the spacers at steep slopes. This is expected since the maximum velocity was only 1.2 ft/s (0.37 m/s) and the maximum depth was 0.56 in (14.2 mm).

The design discharge (q = 0.025 ft^3/s per ft, 0.216 L/s per m) falls through the slot as weir flow without hitting the curb side of the slot. At q = 0.040 ft^3/s per ft (0.345 L/s per m) the flow backs up against the spacers (fig. 83); however, nearly all the flow passes through the slot.

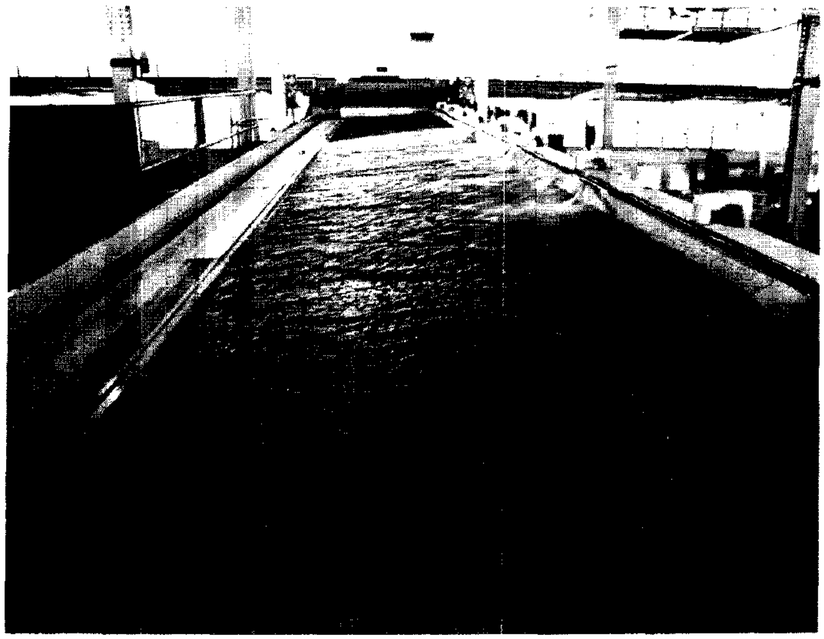


Figure 82. - Sheet flow test So = 0.09, Z = 16, q = 0.040 $ft^3/s/ft$ (0.345 L/s/m).

Figure 83. - Closeup photograph of an SV-1.75-6 slot installation during a sheet flow test. q = 0.040 $ft^3/s/ft$ (0.345 L/s/m), So = 0.09, Z = 16. Notice the flow backing up against the spacers.

CHAPTER 5

PARTIAL FLOW CAPTURE TESTS

Introduction

It is apparent from watching the model operate that more flow enters the slot in the upstream portion than in the downstream portion. Since the water depth is greatest at the start of the slot and becomes progressively more shallow, the upstream portion captures more flow. It follows that it would be more efficient and economical to capture most of the flow in a shorter length of slot and pass the carryover flow on to a downstream collection point.

The purpose of these tests was to determine the efficiency (E = intercepted flow/total flow), of various lengths of slot when a portion of the flow passes the slot. This data was used to determine how much of the total flow is captured by each portion of slot.

Only one type of slot installation was tested in this manner; however, other slot widths and curb distances will be tested and a general slotted drain design procedure will be developed in volume 5. The Federal Highway Administration used information gathered in the total flow capture tests to determine the best configuration to be used for these tests. Figure 84 shows the slot configuration used. Four or five discharges were tested at each slope condition in figure 84, using four different slot lengths. The slot lengths tested were 8, 16, 24, and 32 ft (2.44, 4.88, 7.32, and 9.75 m). Figure 85 is a photograph of a partial flow capture test.

Results

Figures 86 through 97 present the data. Each graph represents one cross slope and one slot length. The graphs compare efficiency (E) to total flow (Q). These plots contain the actual data points. The information in these graphs was plotted in another form in figures 98 through 115. These plots compare slotted drain efficiency to slot lengths for a constant slope condition. Each curve represents a constant discharge from 1 to 5 ft^3/s (0.028 to 0.142 m^3/s). The data for these curves were obtained from the efficiency data, using figures 86 through 97 and the 100 percent capture lengths. In some of the plots, curves were developed using only two data points (8-ft slot length and 100 percent efficiency). The shape of these curves was estimated by observing the shape of curves with similar slope and flow conditions and more data points.

Using figures 98 through 115, the efficiency for any length of slot can be determined for discharges from 1 to 5 ft^3/s (0.028 to 0.142 m^3/s). For example, using figure 102 for a longitudinal slope (So) of 6 percent and a cross slope (1/Z) of 1/16, about 20 ft (6.1 m) of slot would be required to capture 90 percent of 4 ft^3/s (0.113 m^3/s). It would take 28 ft (8.53 m) to capture 100 percent of 4 ft^3/s (0.113 m^3/s). Thus, it takes 40 percent more slot length (28-20)/20 to capture the last 10 percent of the flow. This type of comparison, along with the installation costs for a particular site, can be used to determine the most economical installation.

Another advantage of a partial capture approach is shown in figure 115. For this severe slope condition (So = 9 percent and Z = 48), the maximum flow which can be entirely captured in 48 ft (14.6 m) of slot is 0.3 ft^3/s (0.008 m^3/s) (see fig. 16). This would indicate that it is not feasible to use slotted drains at this slope condition. However, 80 percent of 1.00 ft^3/s (0.028 m^3/s) or 0.80 ft^3/s (0.023 m^3/s) is captured by 28 ft (8.53 m) of slot. This information would make it possible to use slotted drain for severe slope conditions where it would not be feasible to capture all of the flow.

Additional curves can be added to figures 98 through 115 for any constant discharge. The data for the required discharge and slope condition would be transferred from figures 86 through 97 to the graph for the desired slope condition.

Figures 116 and 117 are photographs of additional partial flow capture tests.

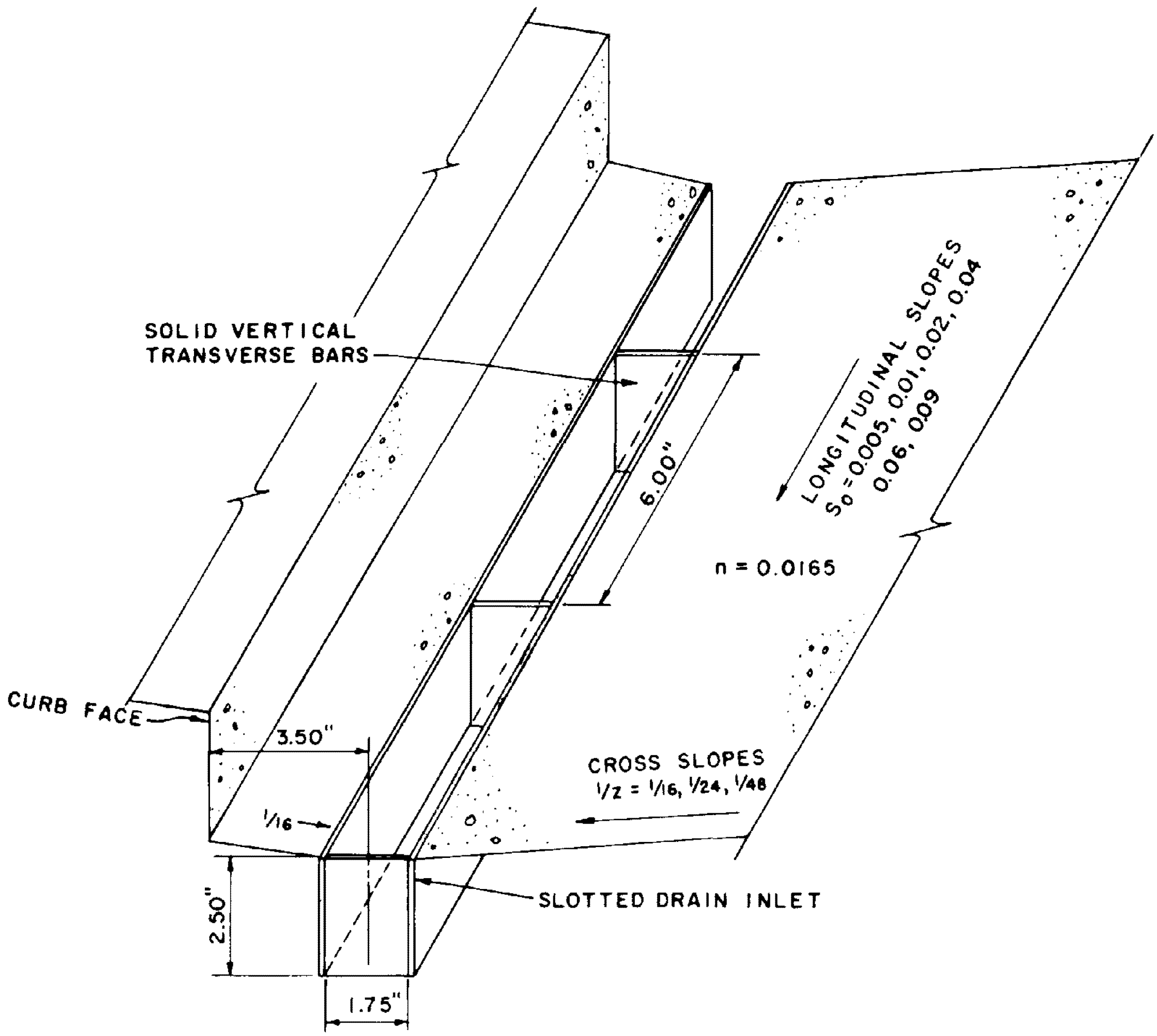


Figure 84. - Standard slot configuration for partial flow capture tests. (1 inch = 25.4 mm, 1 foot = 0.3048 m)

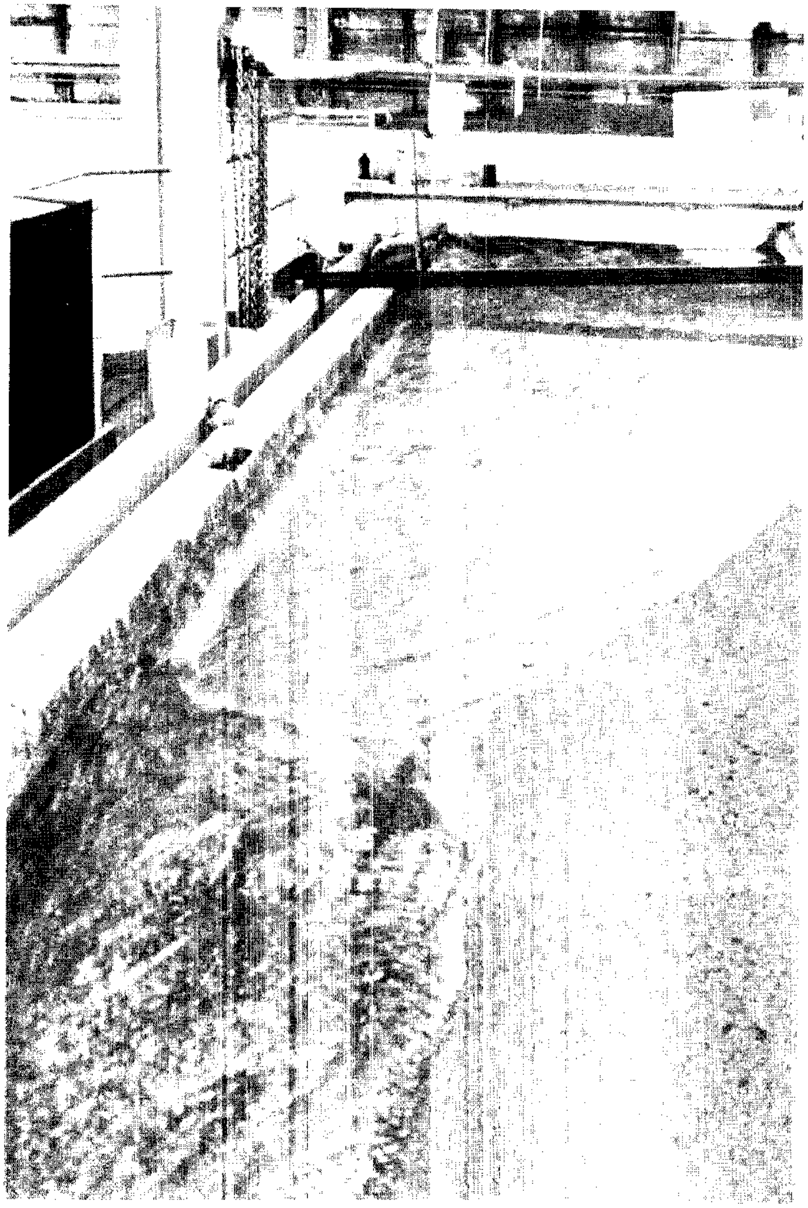


Figure 85. - Partial flow capture test - LA = 16 ft (4.9 m), So = 0.04, Z = 16, Q = 4.22 ft^3/s (0.12 m^3/s), E = 82 percent. L for 100 percent capture = 25 ft (7.6 m).

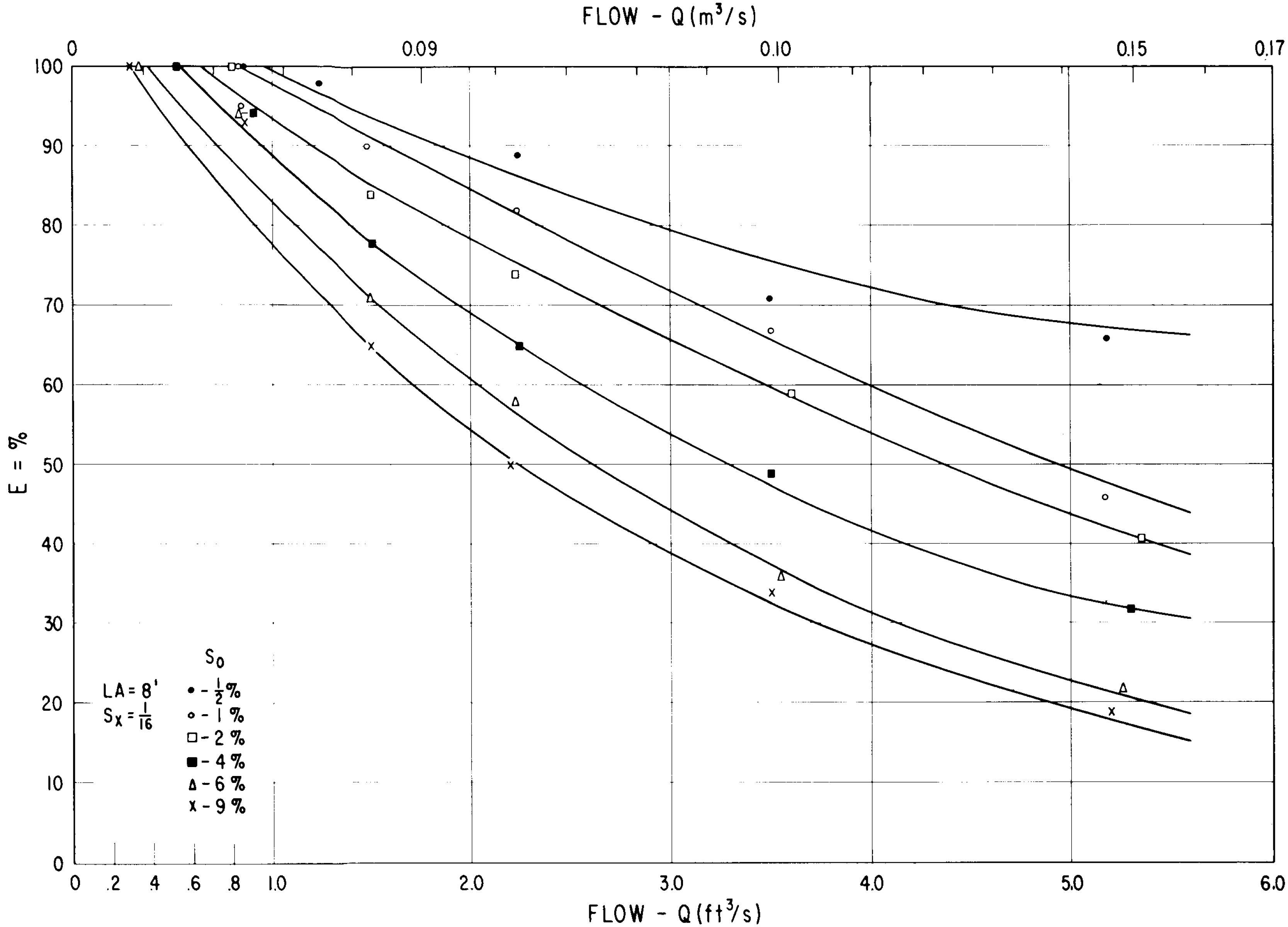


Figure 86. - Efficiency vs. discharge Z = 16, LA = 8 ft (2.44 m).

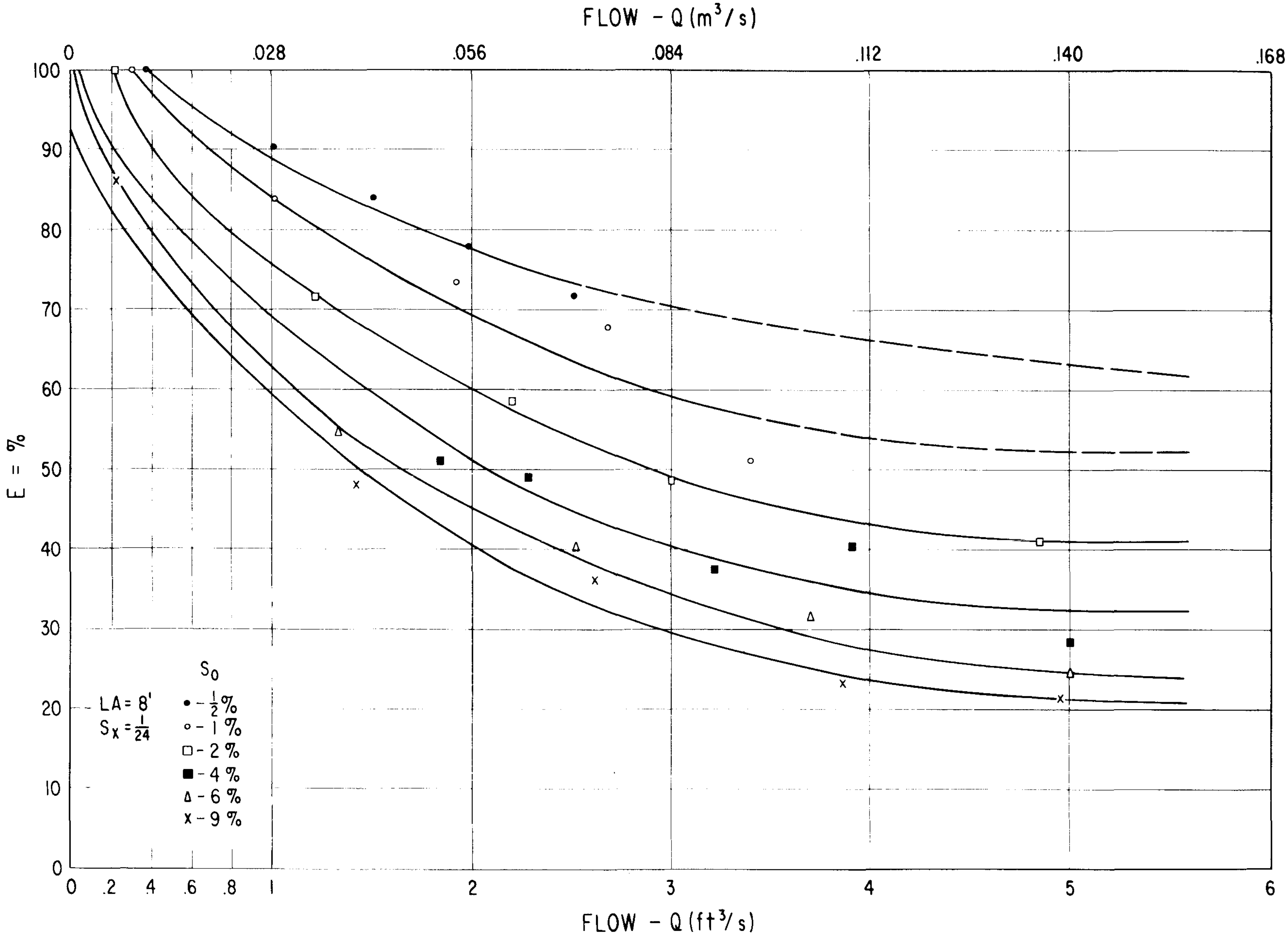


Figure 87. - Efficiency vs. discharge Z = 24, LA = 8 ft (2.44 m).

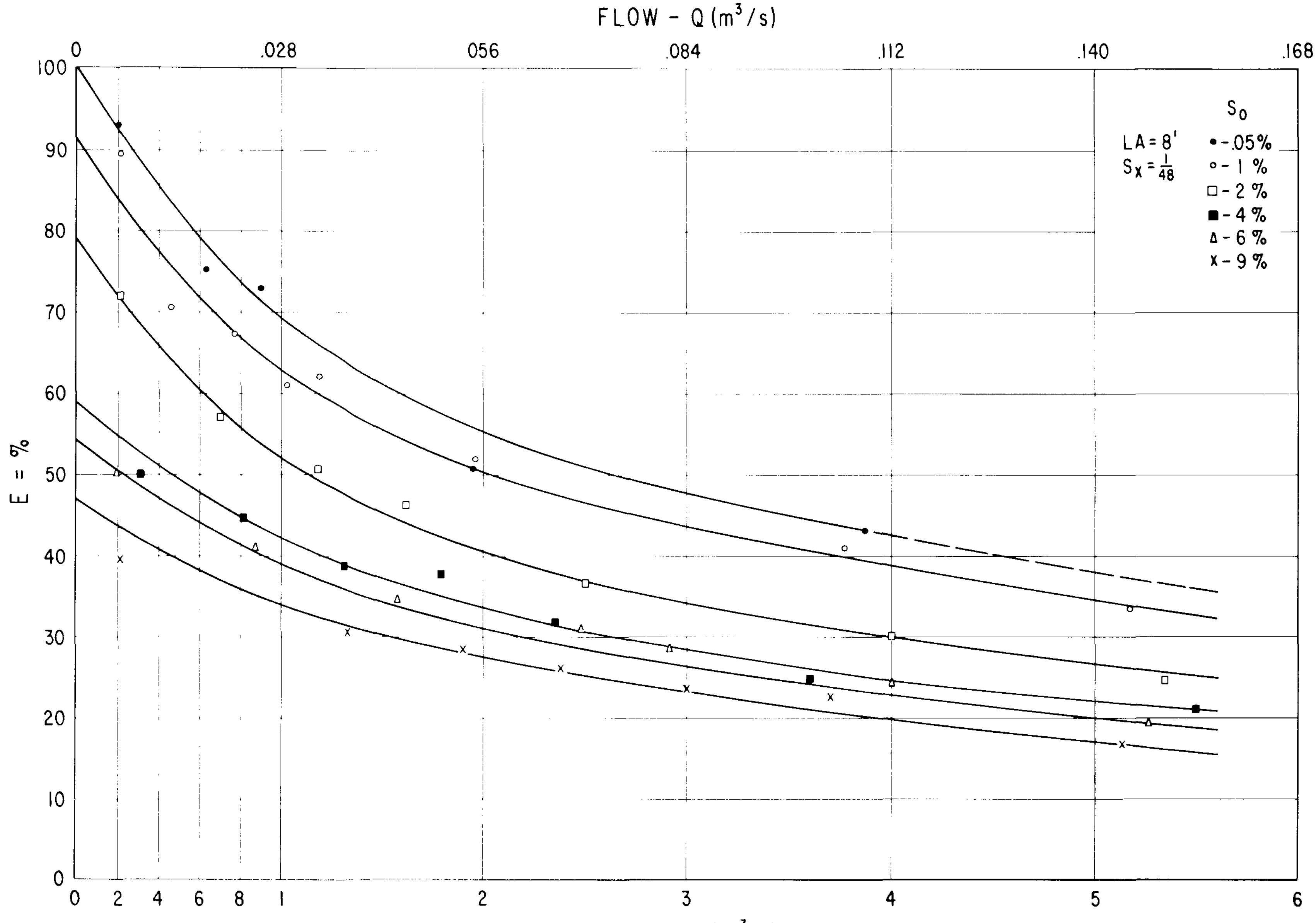


Figure 88. - Efficiency vs. discharge Z = 48, LA = 8 ft (2.44 m).

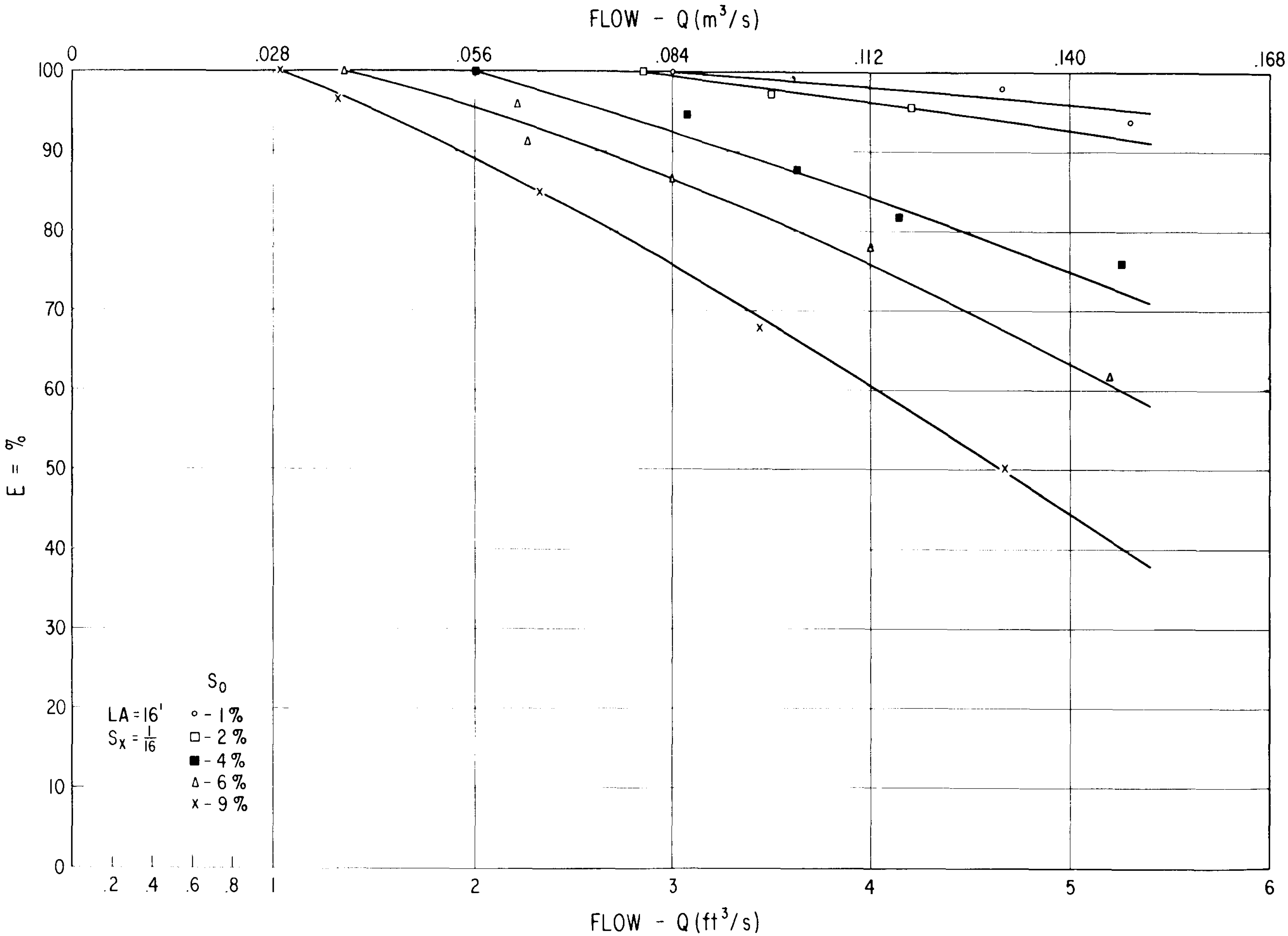


Figure 89. - Efficiency vs. discharge Z = 16, LA = 16 ft (4.88 m).

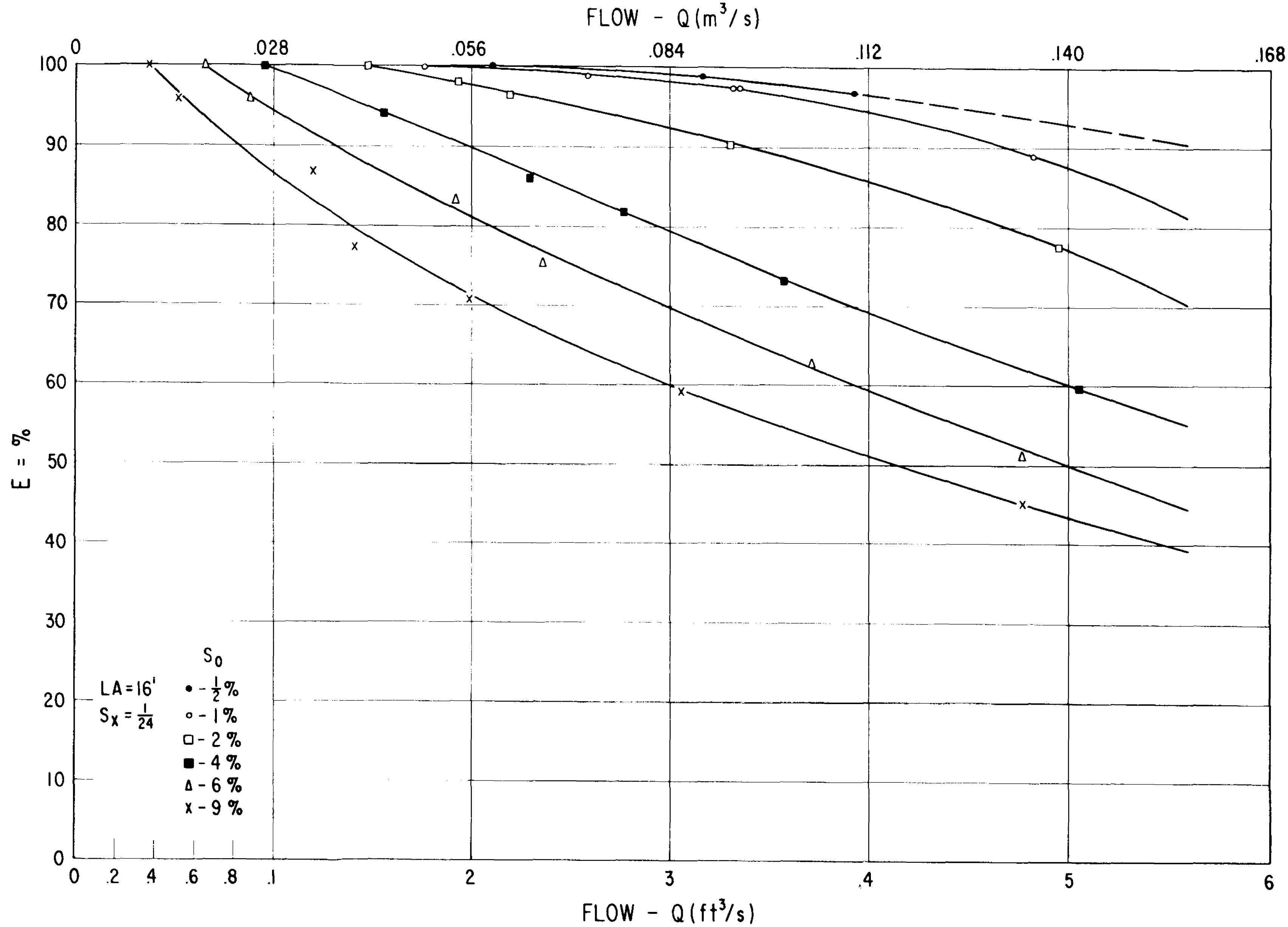


Figure 90. - Efficiency vs. discharge Z = 24, LA = 16 ft (4.88 m).

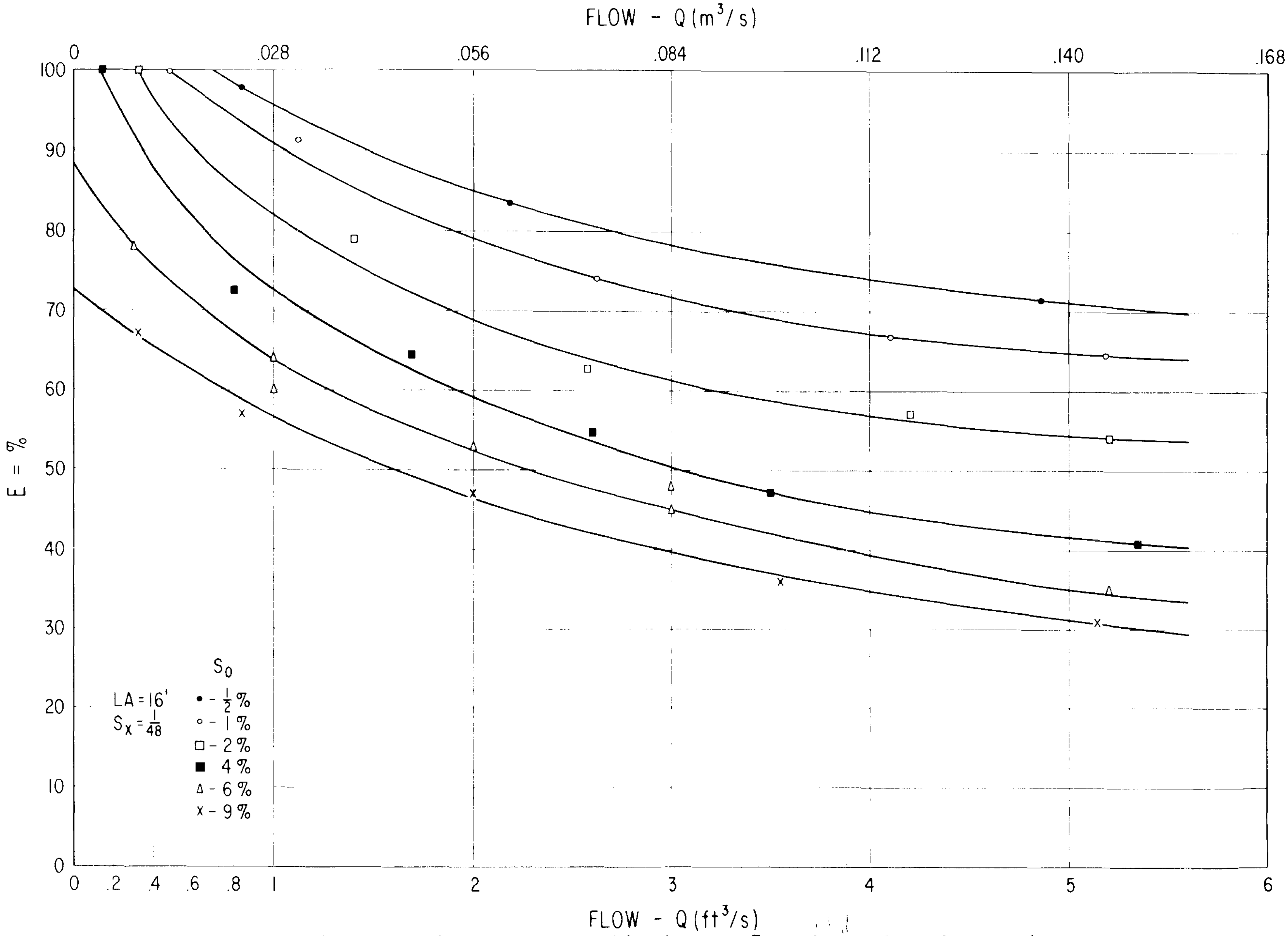


Figure 91. - Efficiency vs. discharge Z = 48, LA = 16 ft (4.88 m).

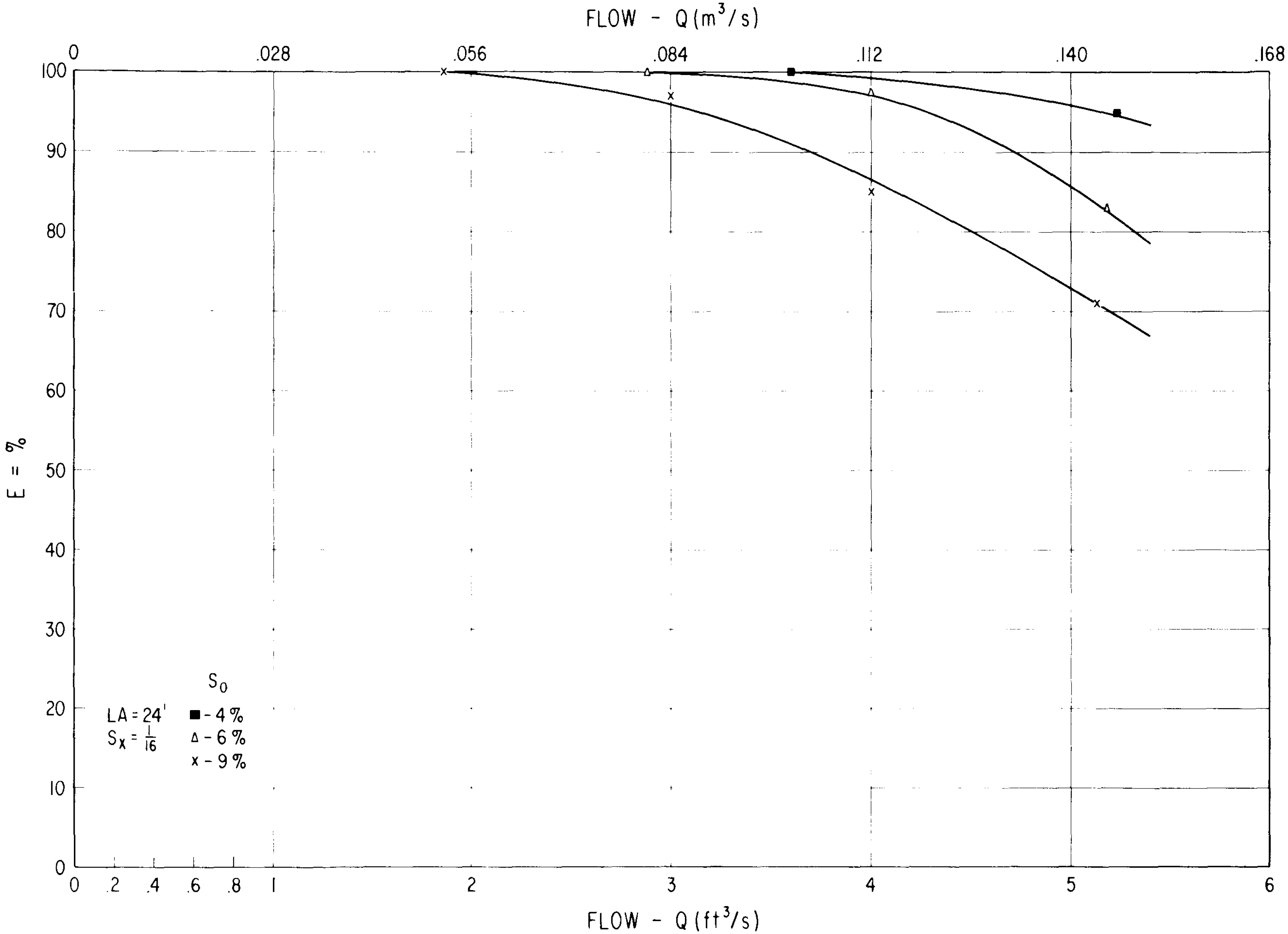


Figure 92. - Efficiency vs. discharge Z = 16, LA = 24 ft (7.32 m).

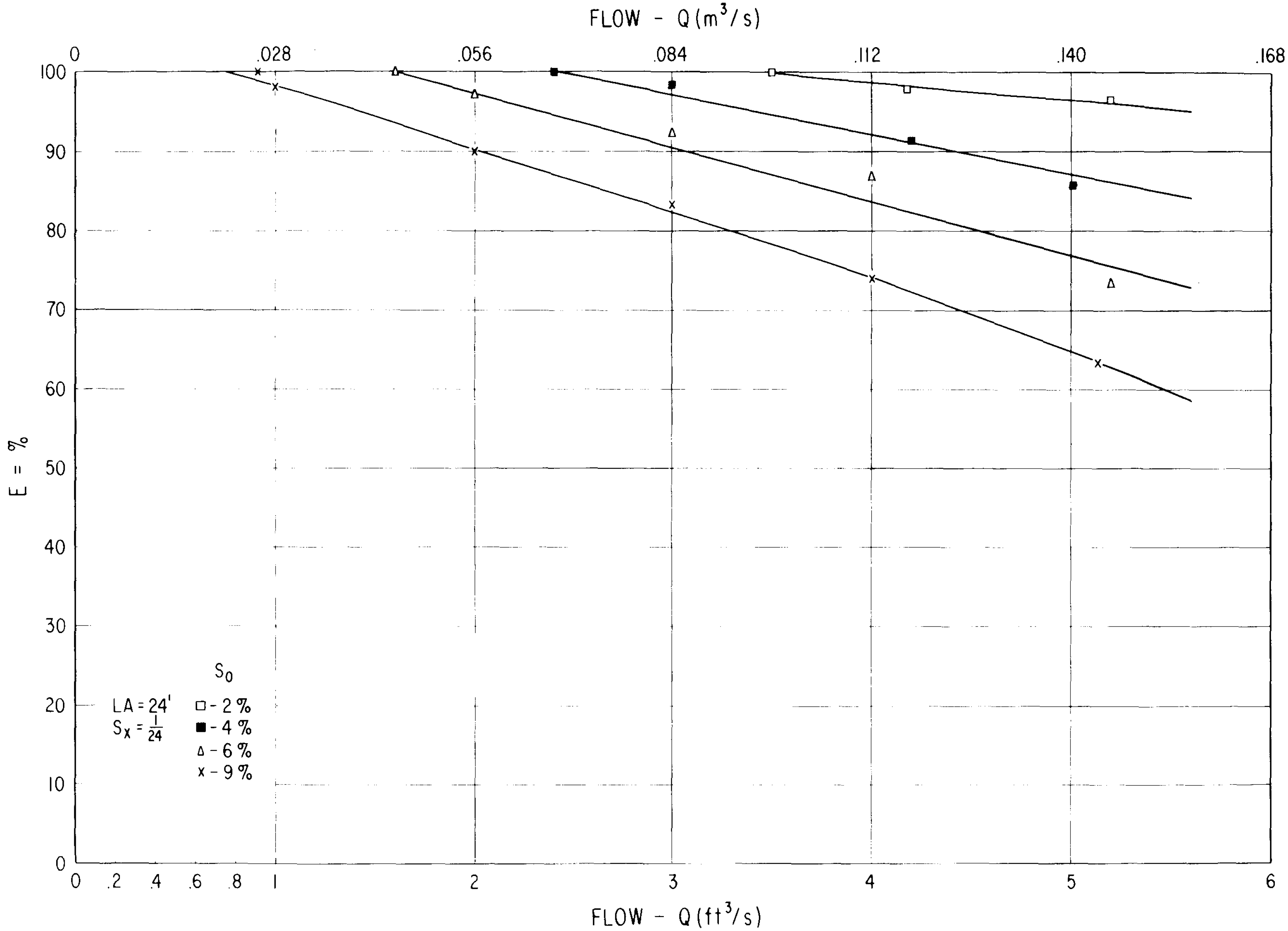


Figure 93. - Efficiency vs. discharge Z = 24, LA = 24 ft (7.32 m).

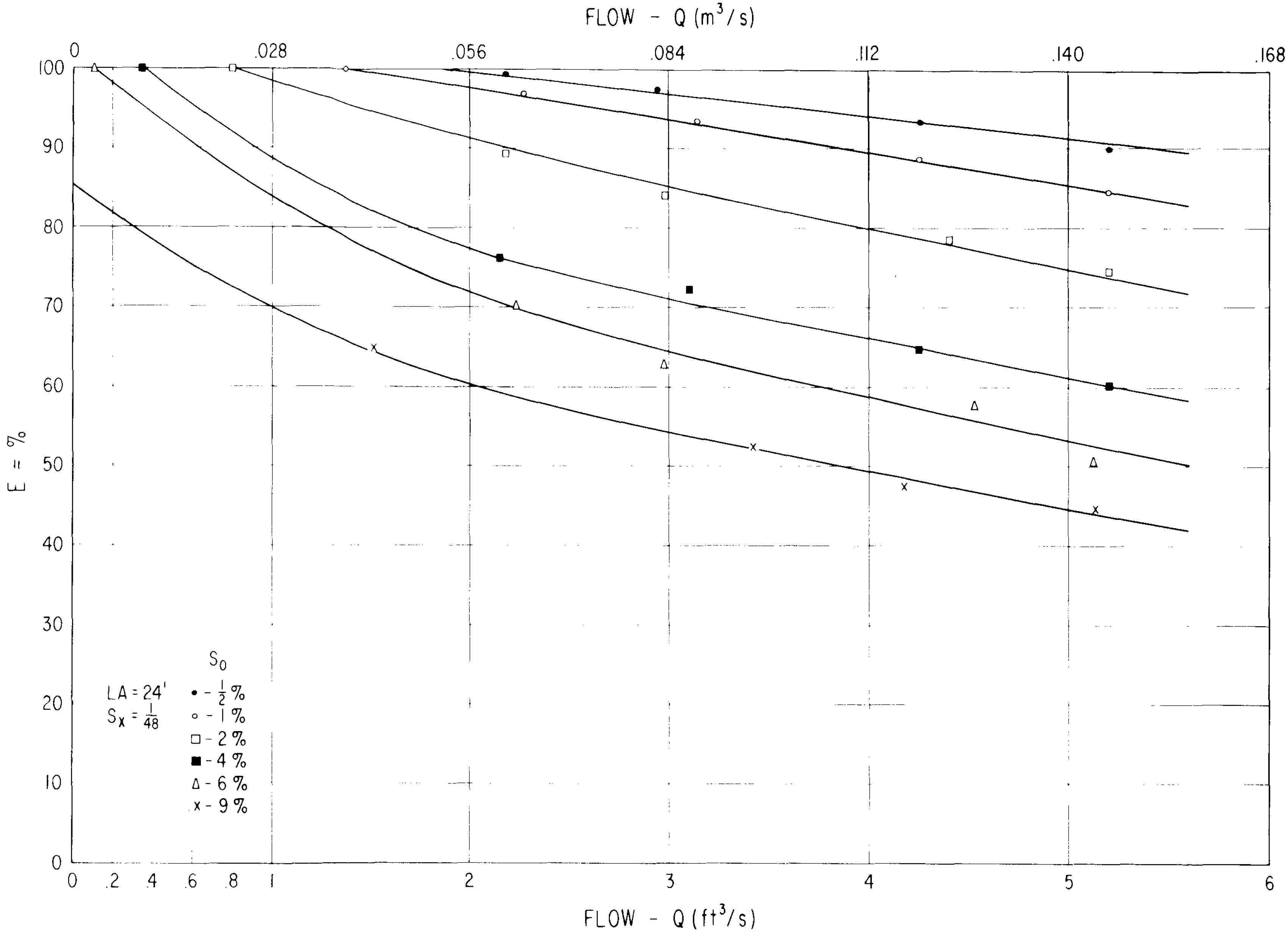


Figure 94. - Efficiency vs. discharge Z = 48, LA = 24 ft (7.32 m).

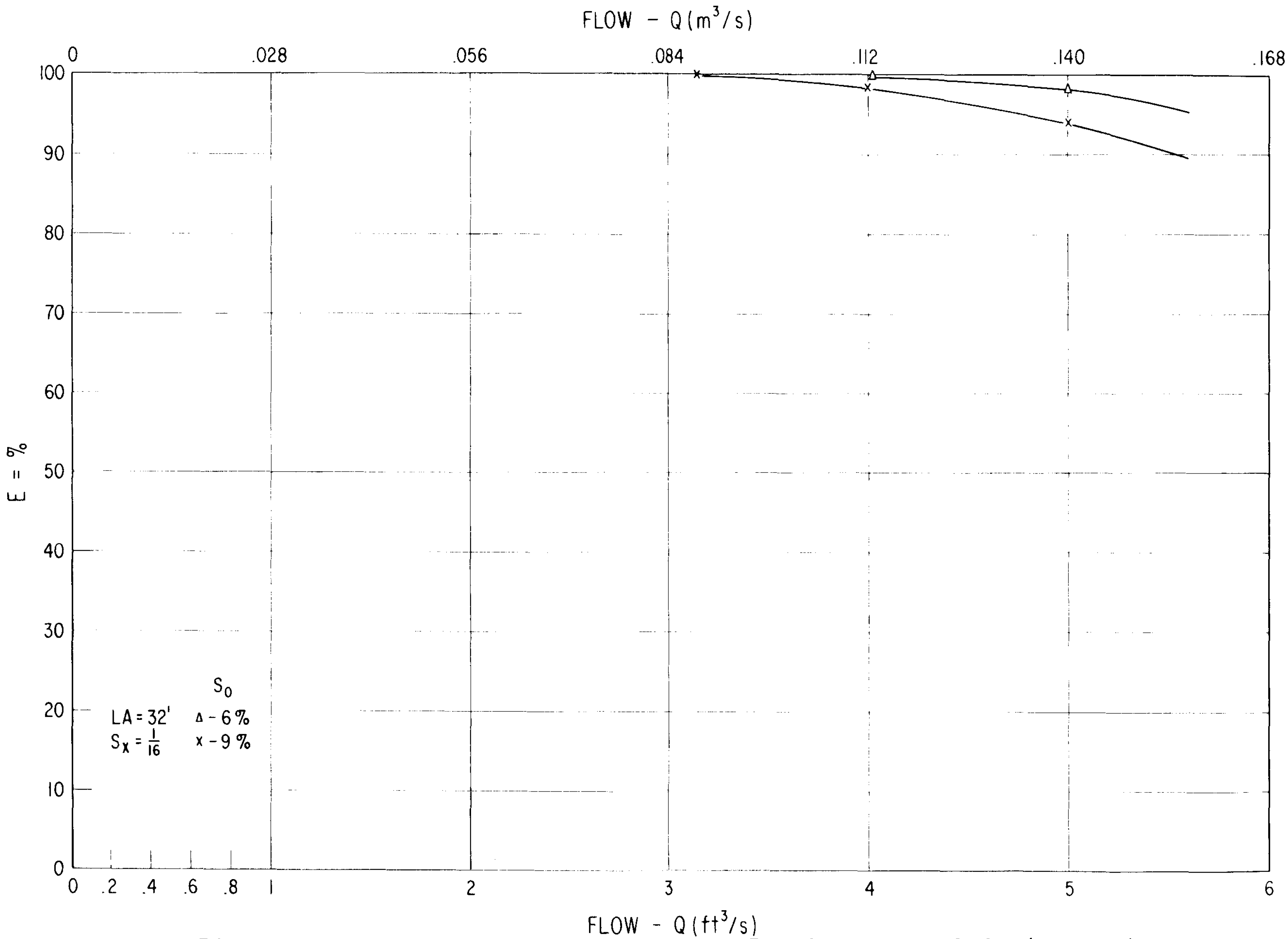


Figure 95. - Efficiency vs. discharge Z = 16, LA = 32 ft (9.75 m).

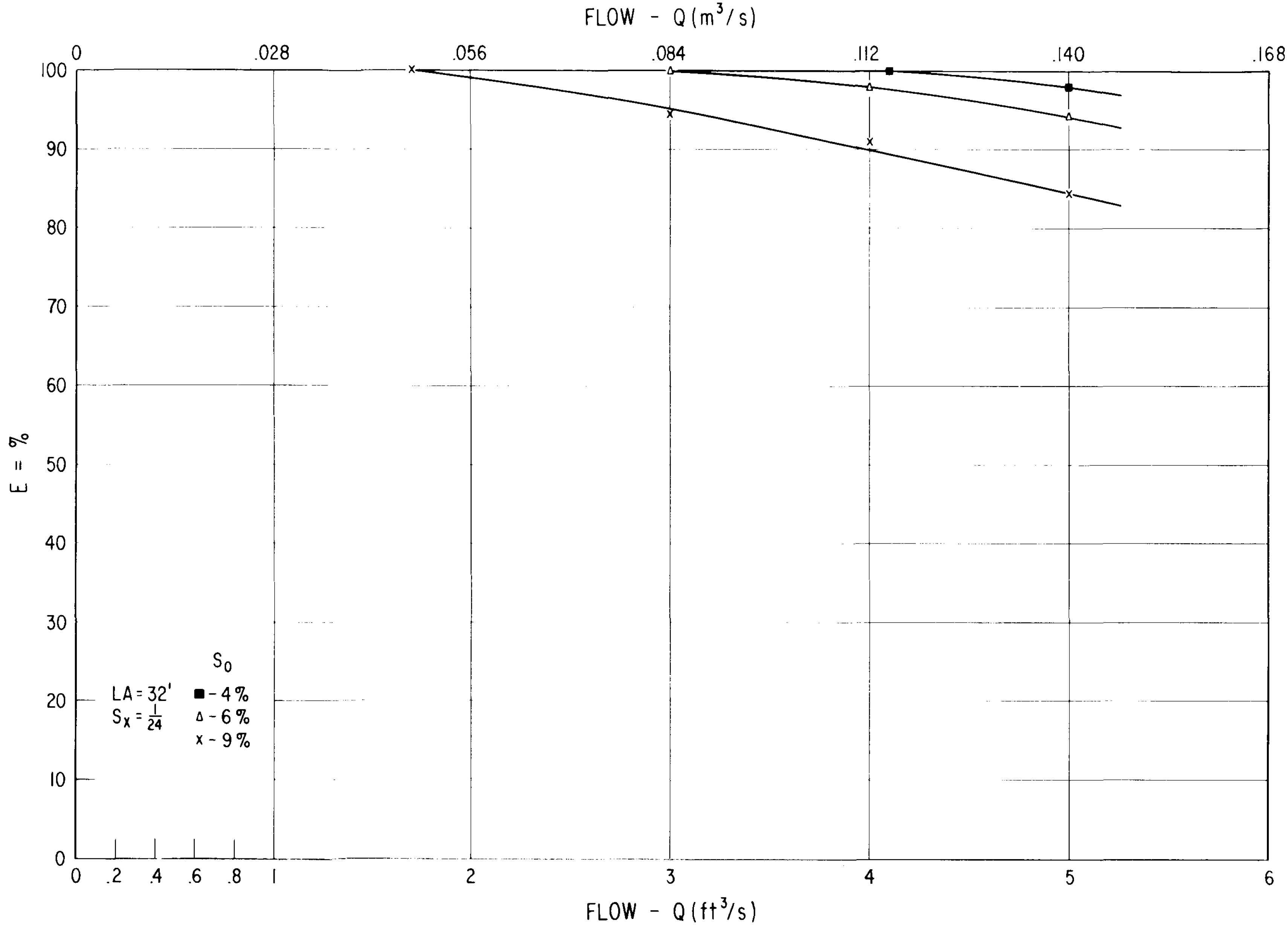


Figure 96. - Efficiency vs. discharge Z = 24, LA = 32 ft (9.75 m).

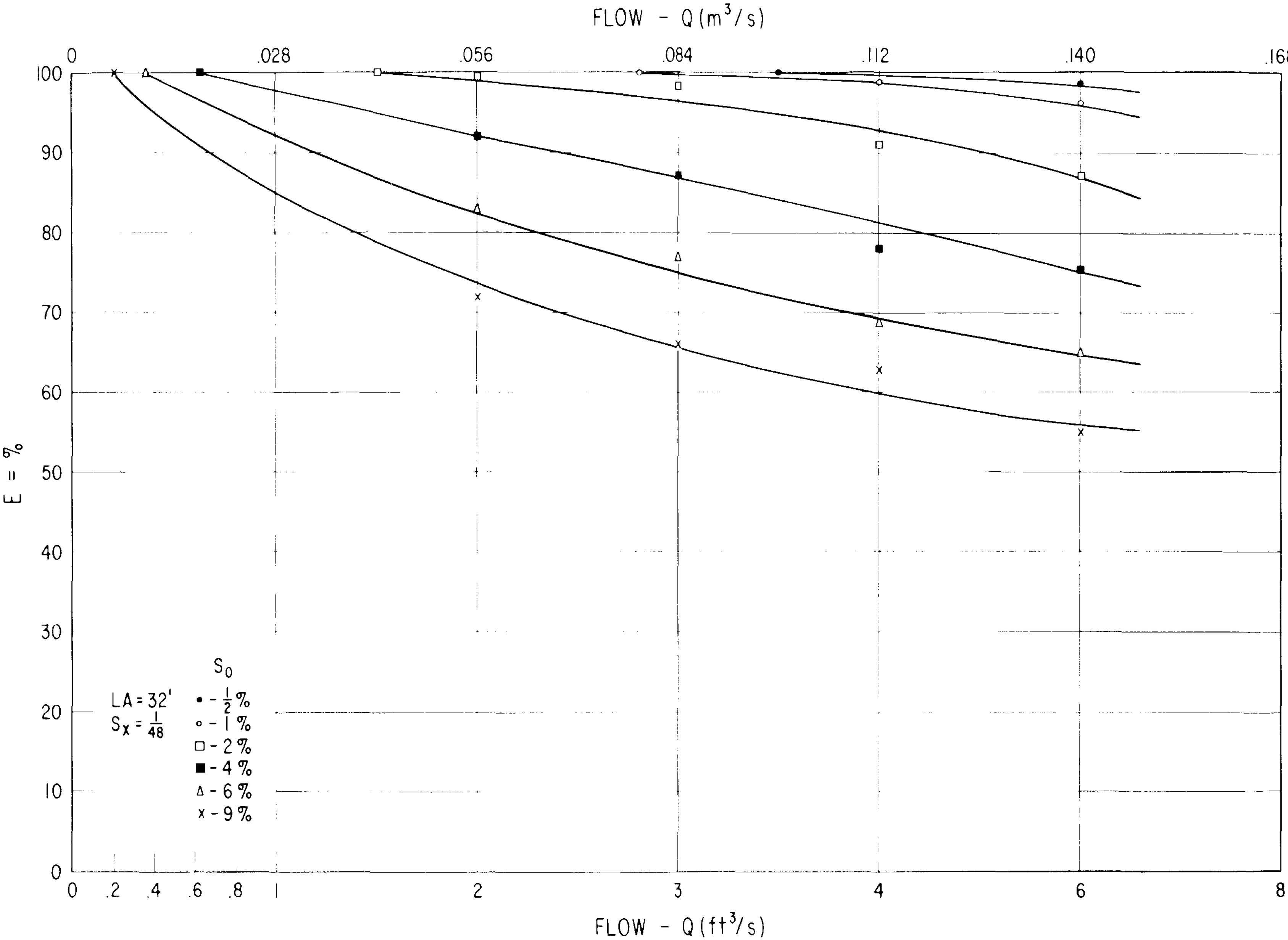


Figure 97. - Efficiency vs. discharge Z = 48, LA = 32 ft (9.75 m).

SLOTTED DRAIN-EFFICIENCY VS SLOT LENGTH

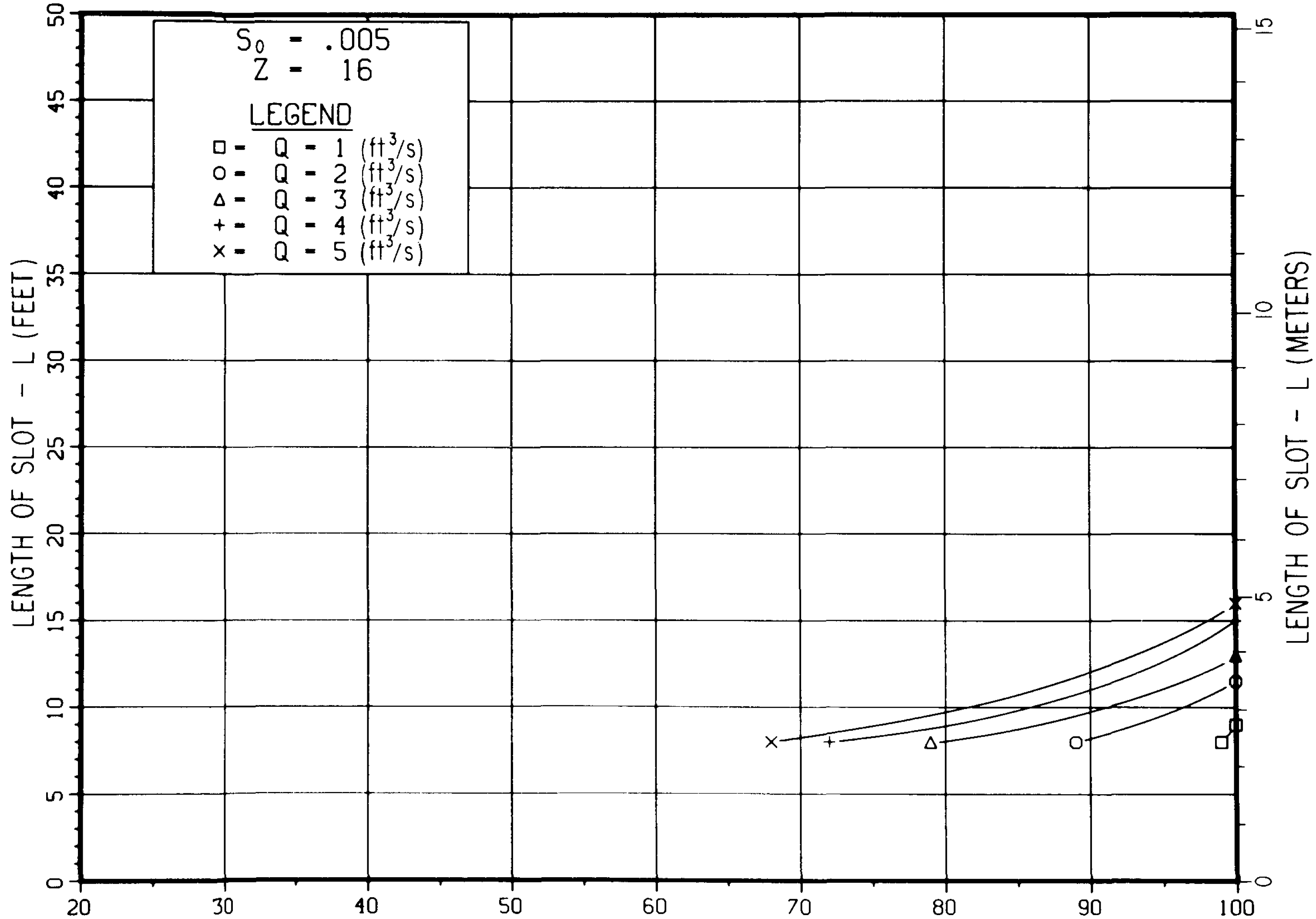


Figure 98. - Efficiency vs. slot length So = 0.005, Z = 16.

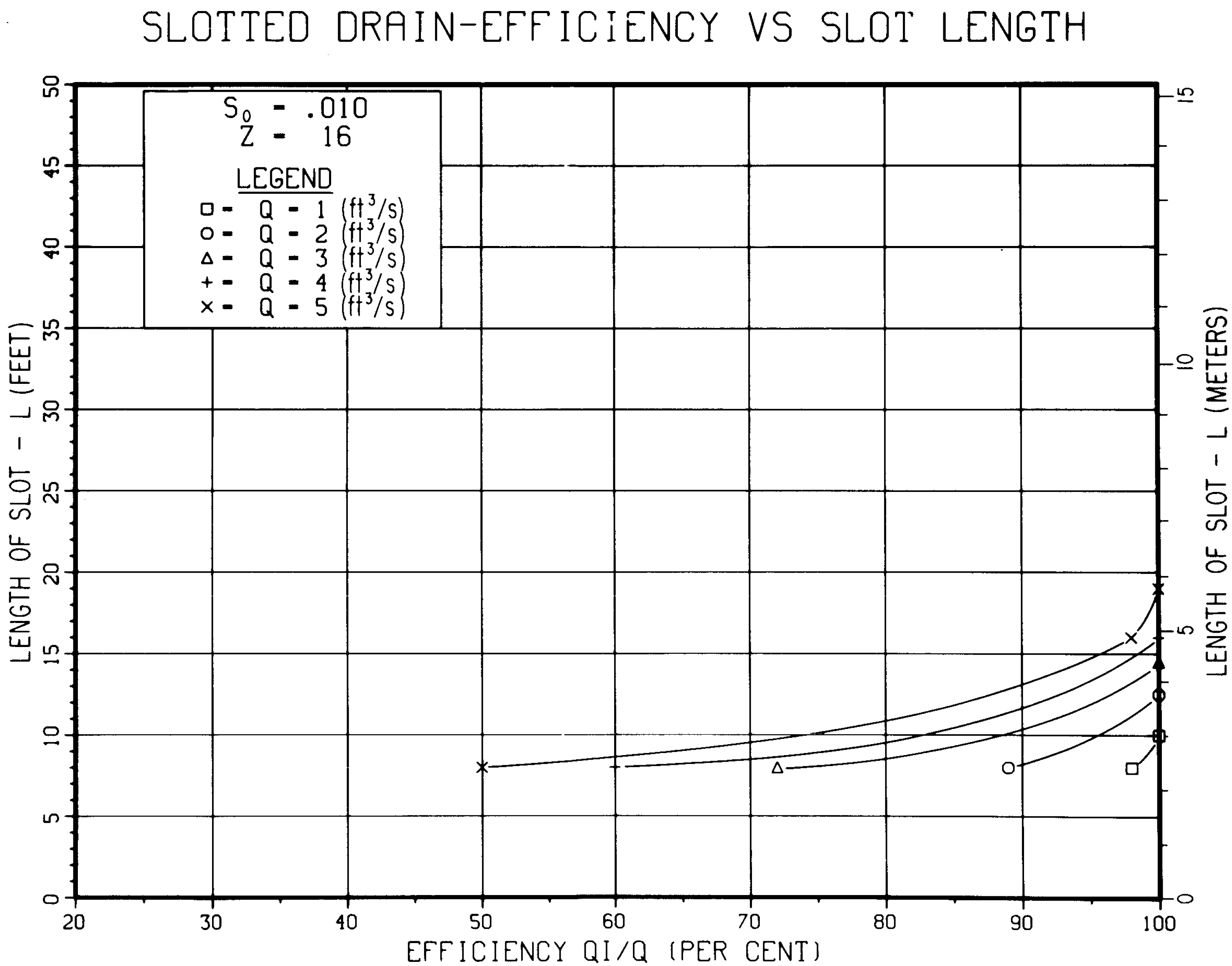


Figure 99. - Efficiency vs. slot length So = 0.01, Z = 16.

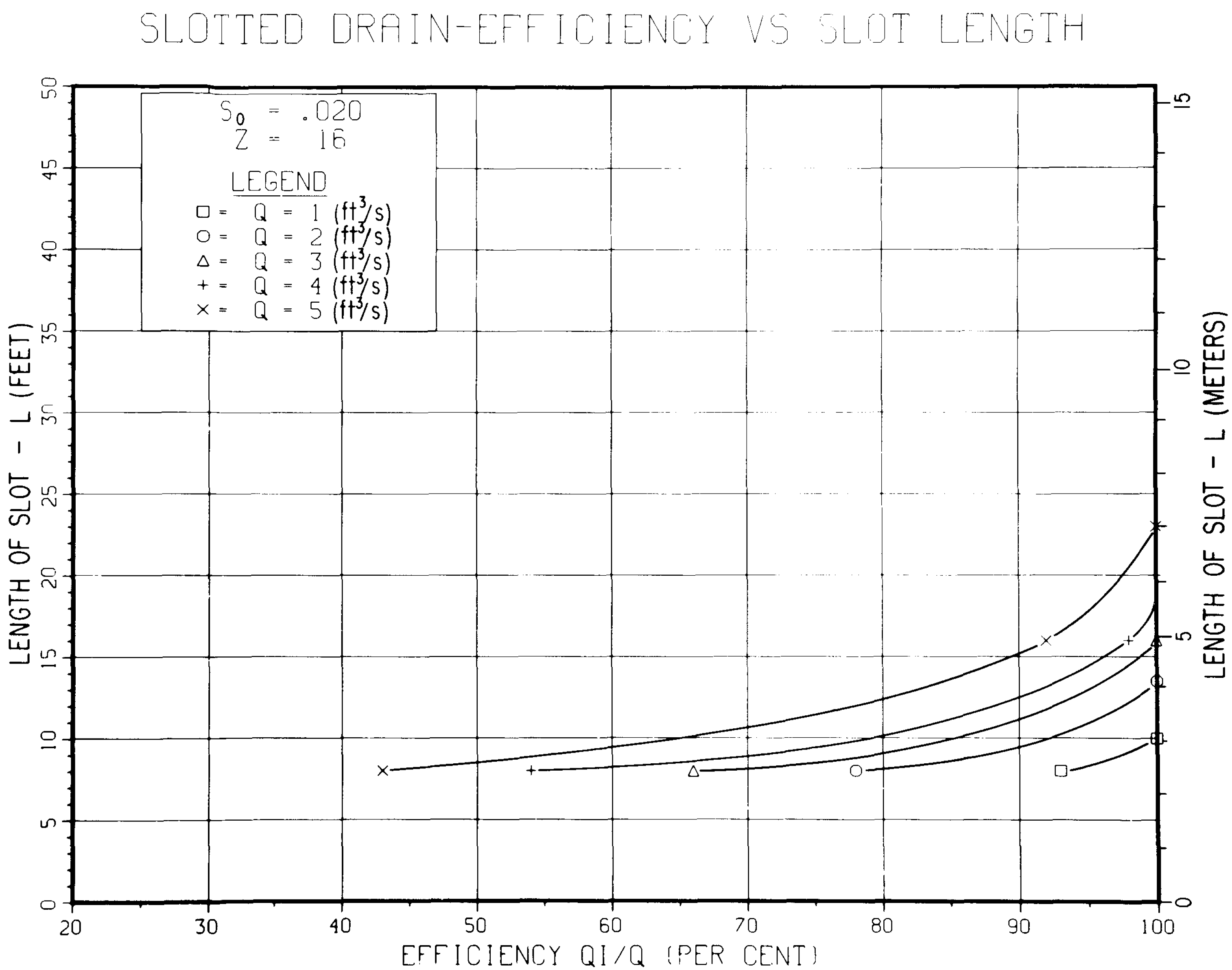


Figure 100. - Efficiency vs. slot length So = 0.02, Z = 16.

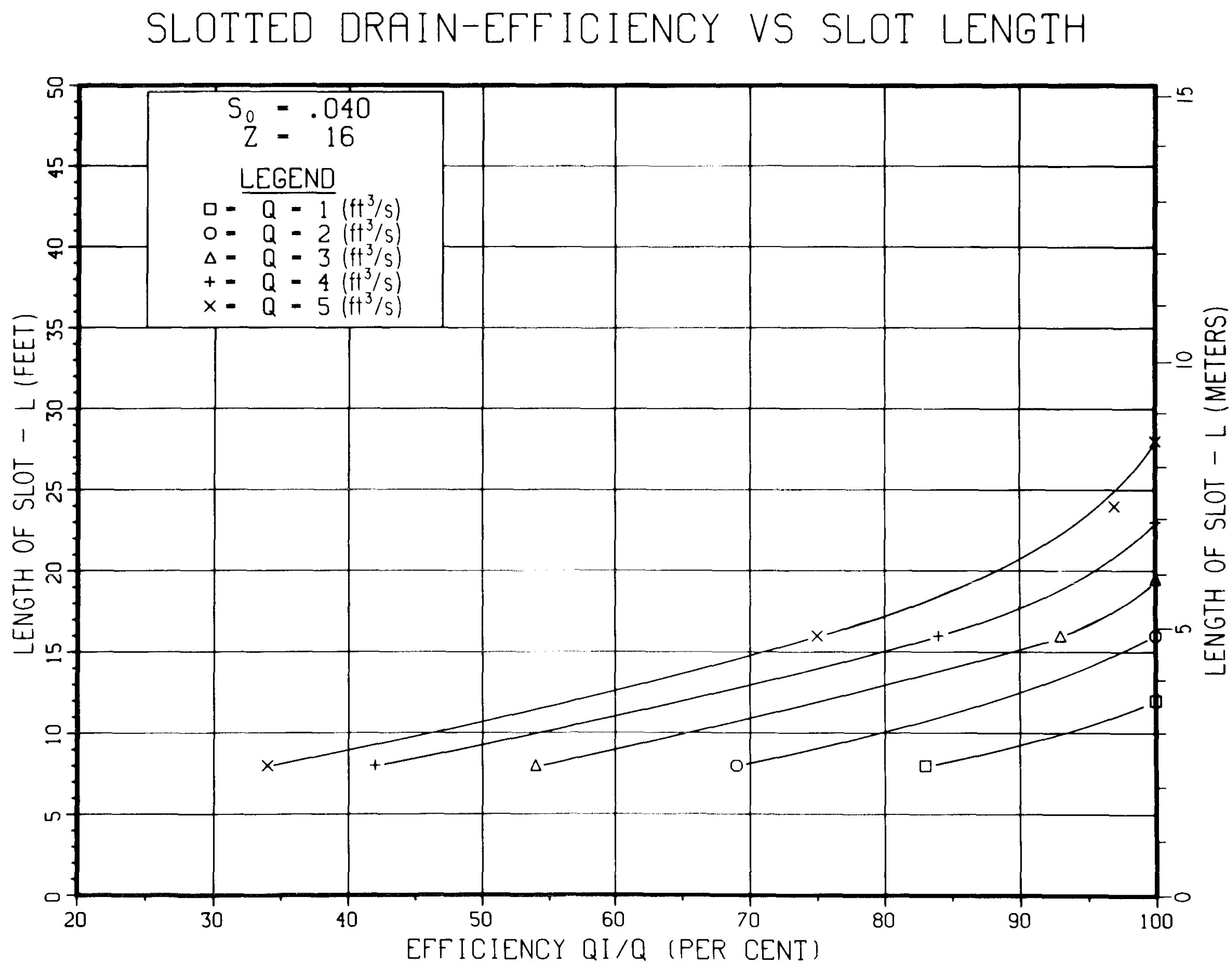


Figure 101. - Efficiency vs. slot length So = 0.04, Z = 16.

SLOTTED DRAIN-EFFICIENCY VS SLOT LENGTH

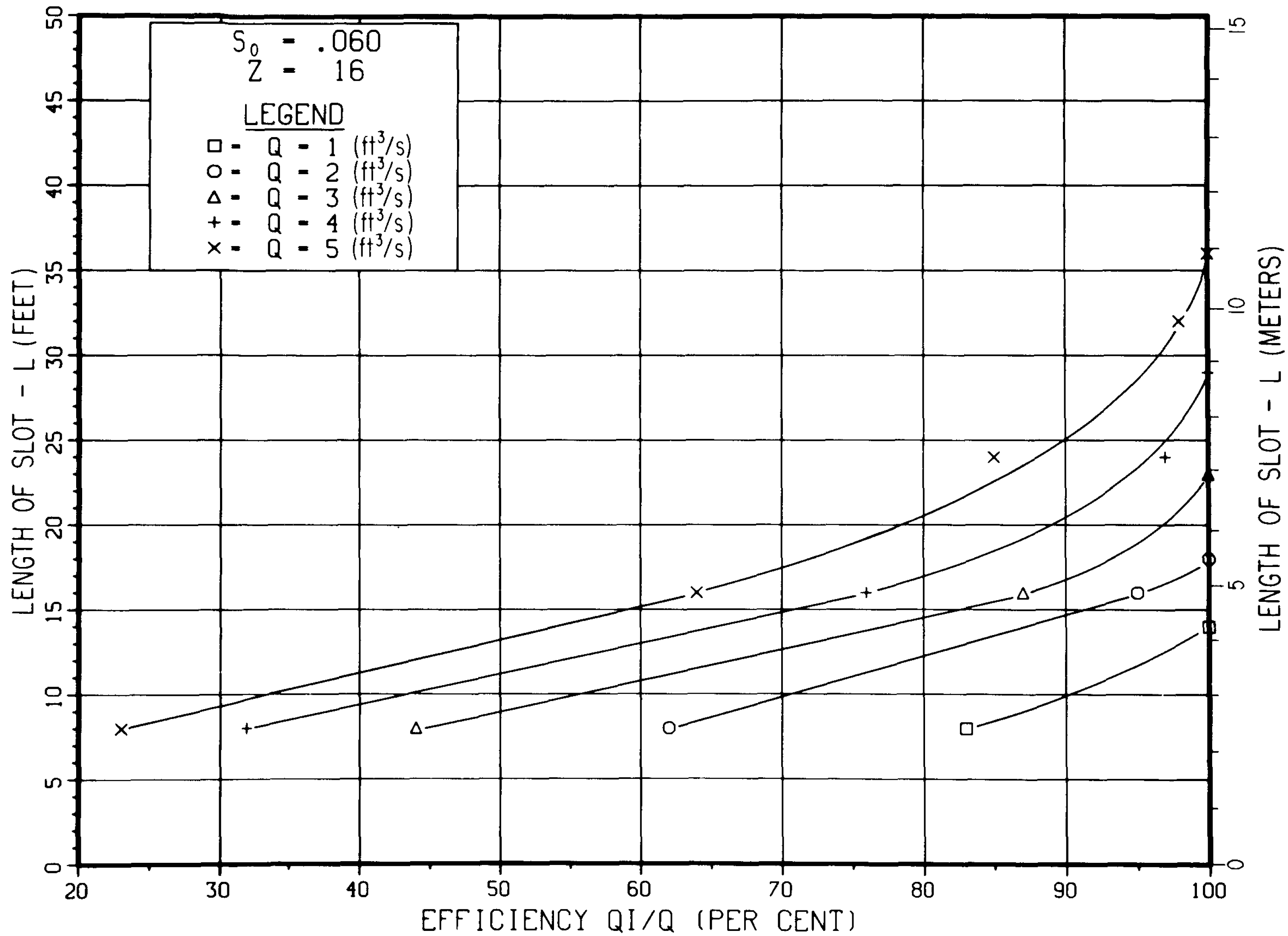


Figure 102. - Efficiency vs. slot length So = 0.06, Z = 16.

SLOTTED DRAIN-EFFICIENCY VS SLOT LENGTH

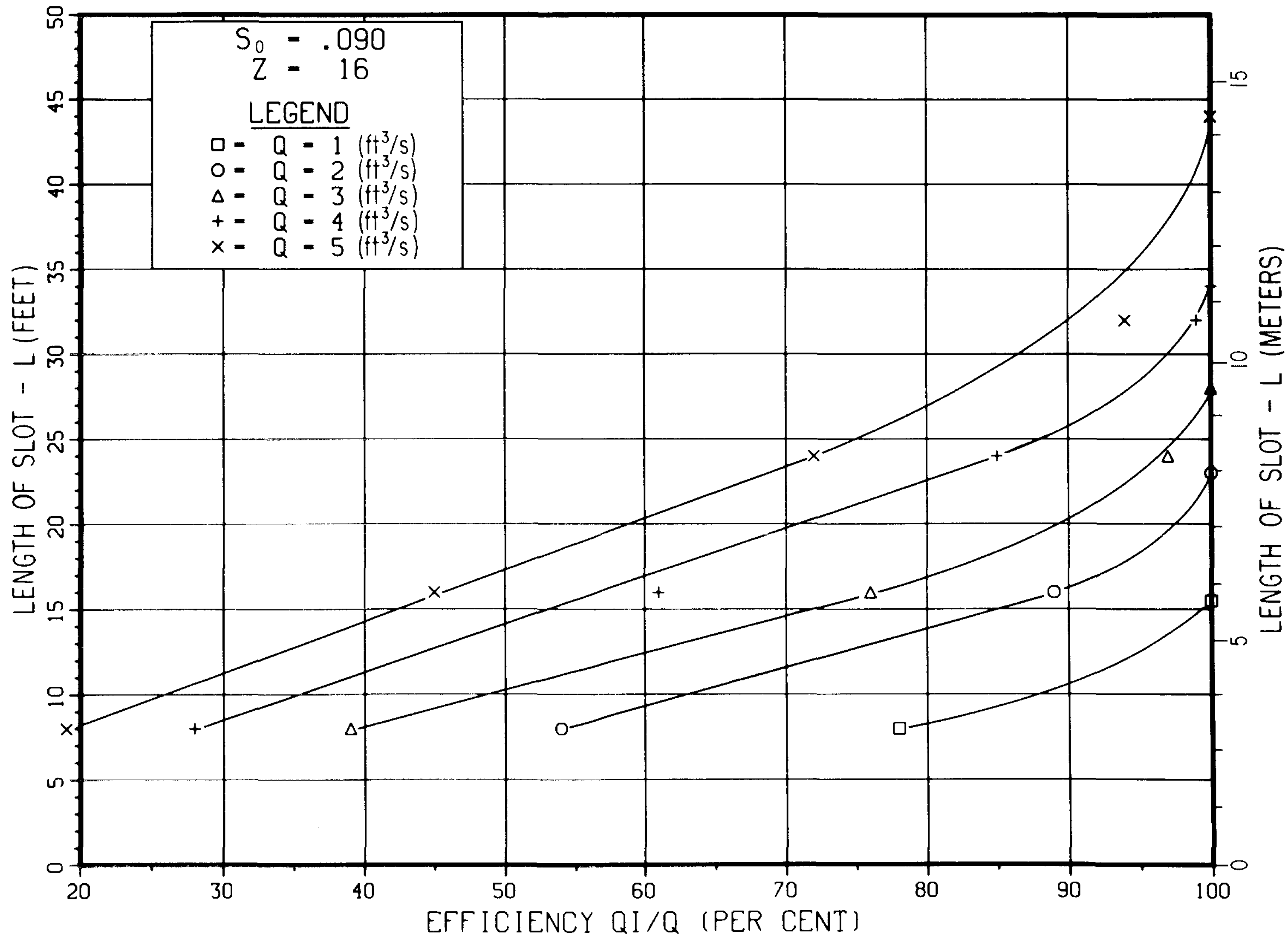


Figure 103. - Efficiency vs. slot length So = 0.09, Z = 16.

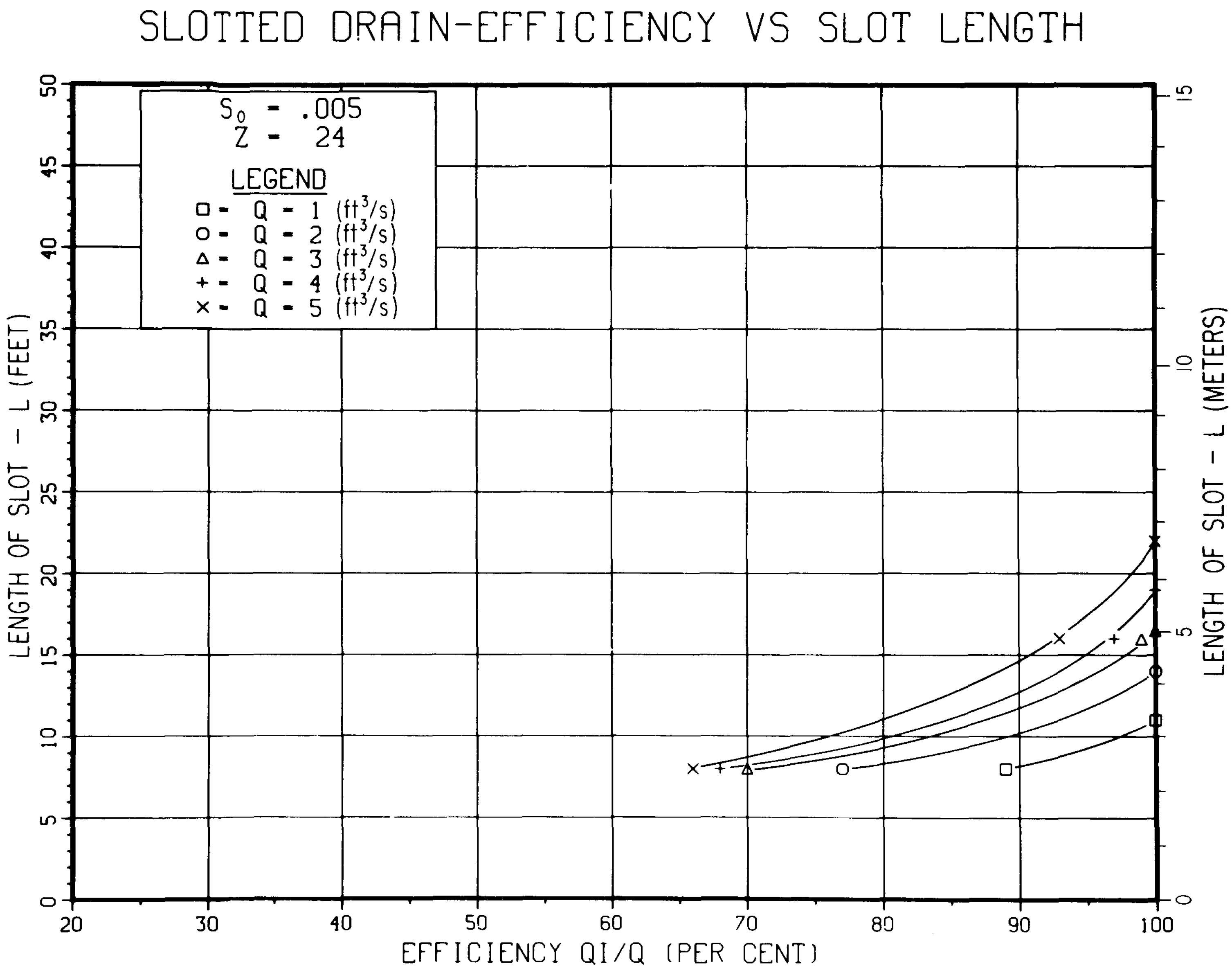


Figure 104. - Efficiency vs. slot length So = 0.005, Z = 24.

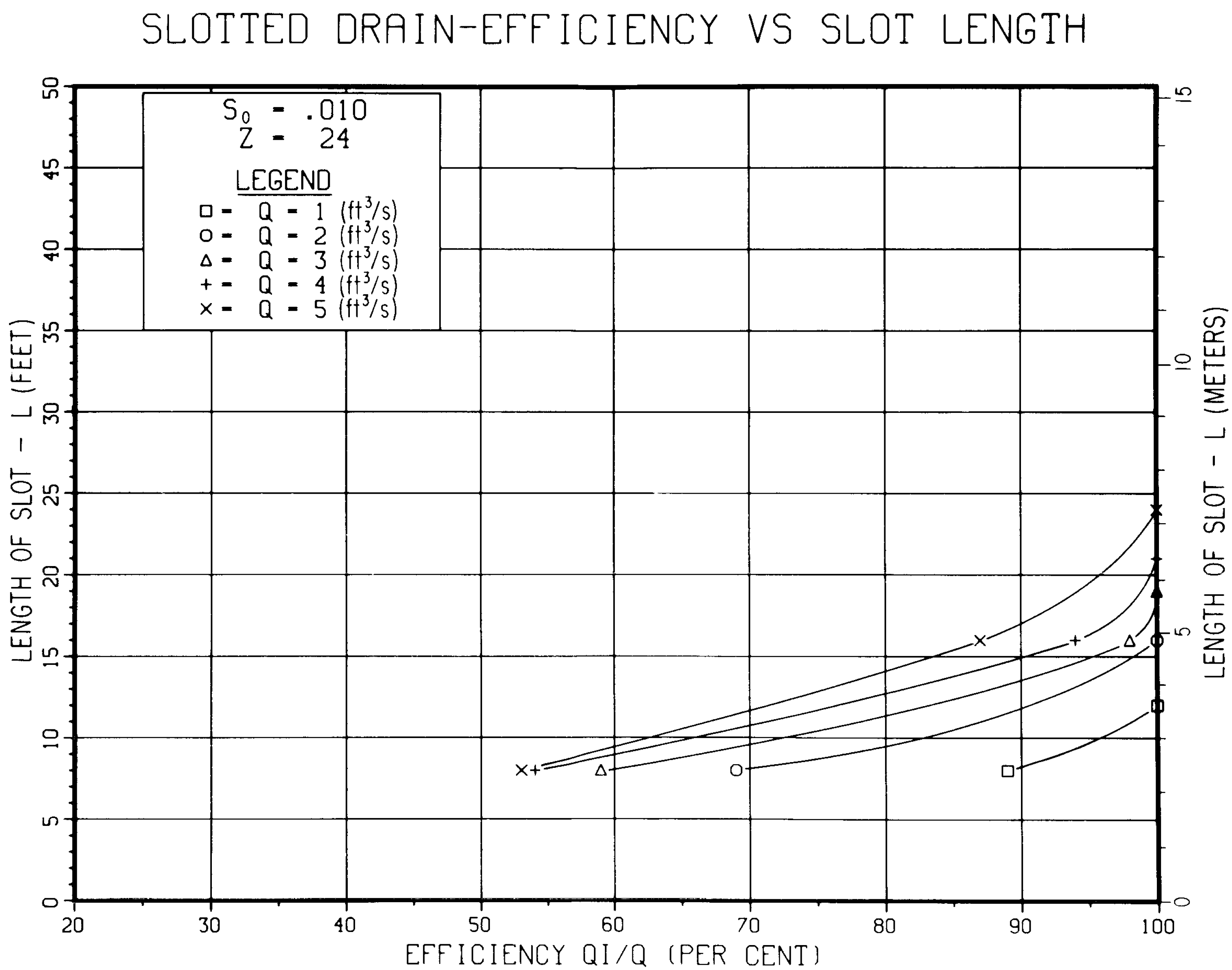


Figure 105. - Efficiency vs. slot length So = 0.01, Z = 24.

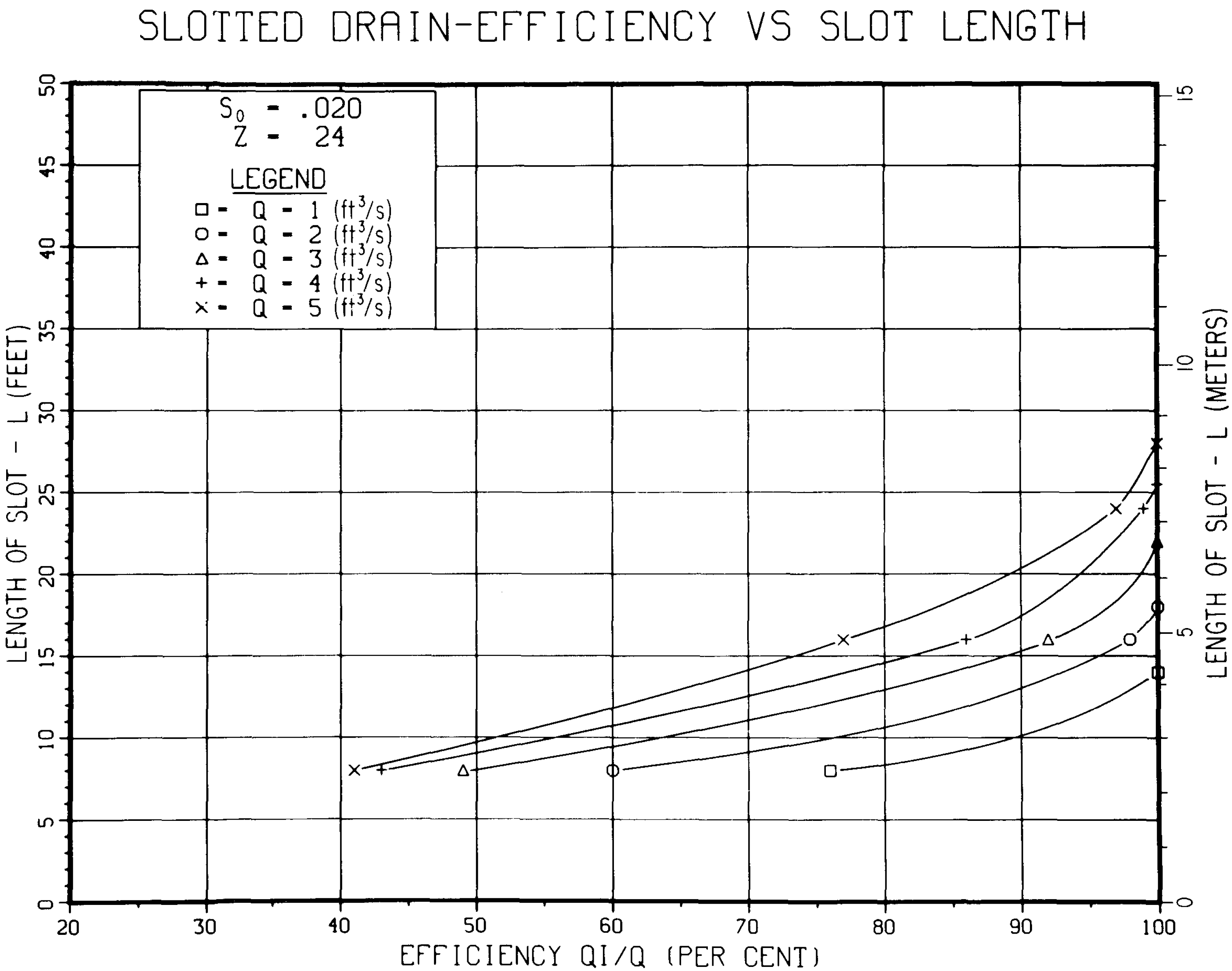


Figure 106. - Efficiency vs. slot length So = 0.02, Z = 24.

SLOTTED DRAIN-EFFICIENCY VS SLOT LENGTH

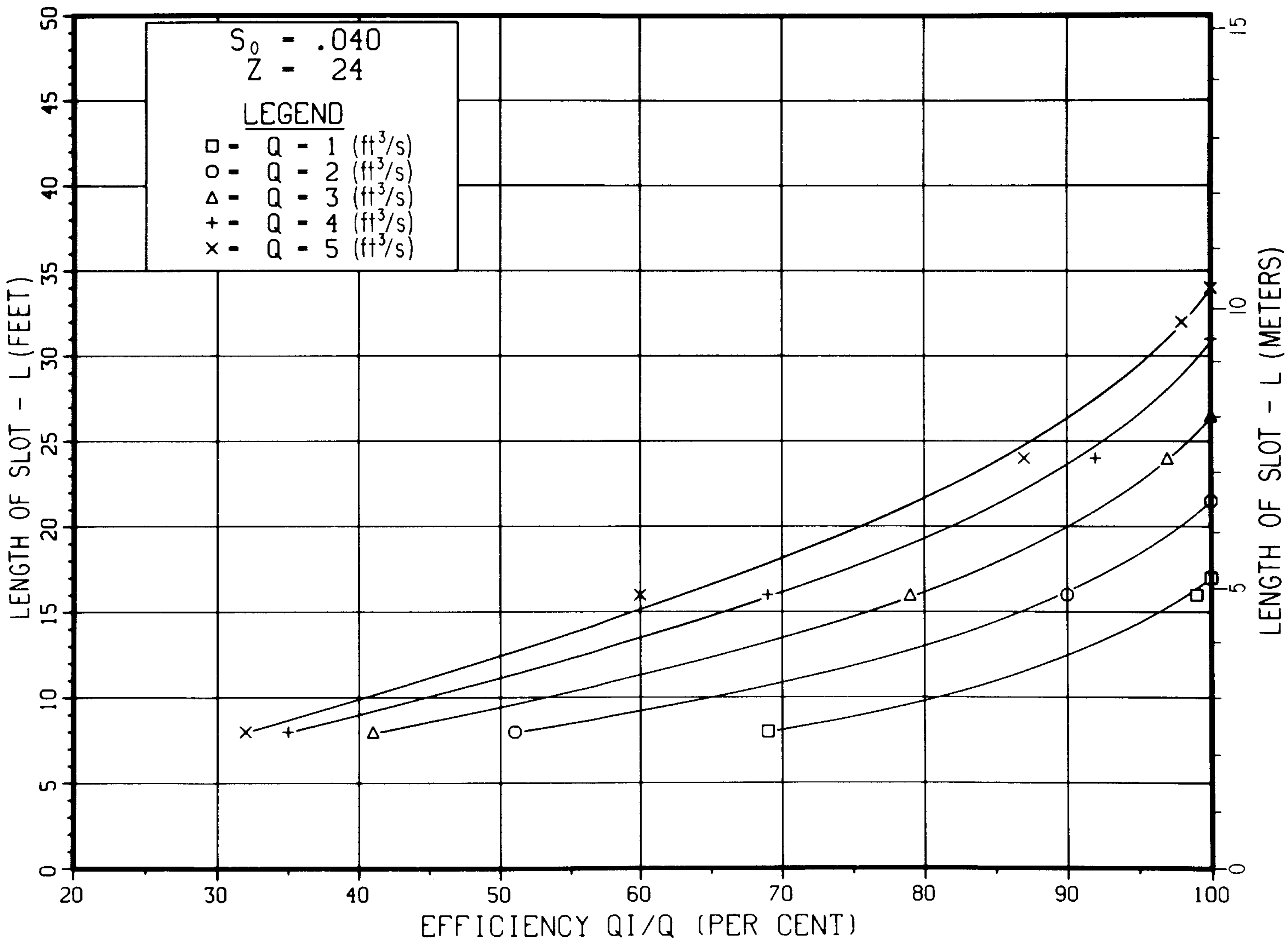


Figure 107. - Efficiency vs. slot length So = 0.04, Z = 24.

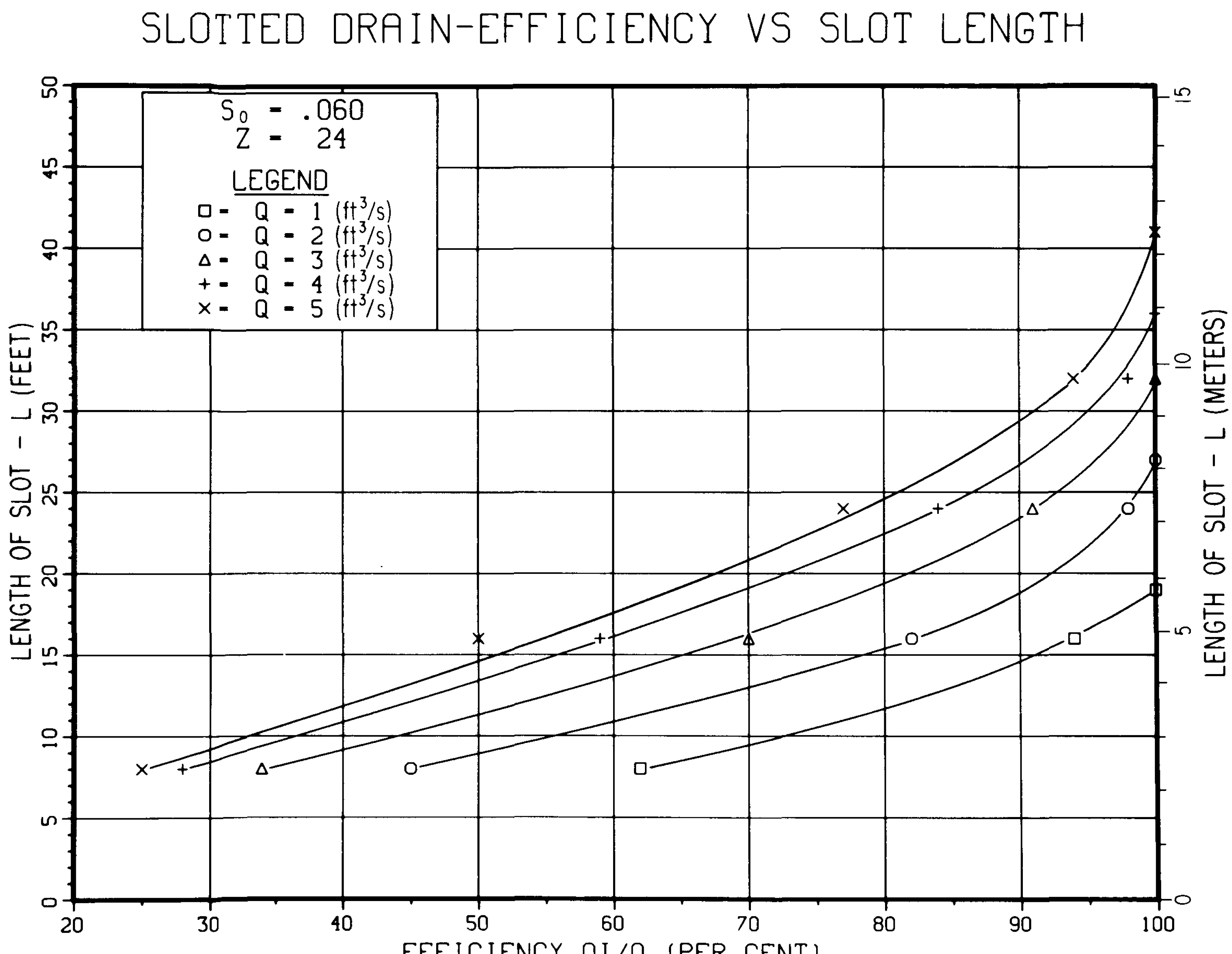


Figure 108. - Efficiency vs. slot length So = 0.06, Z = 24.

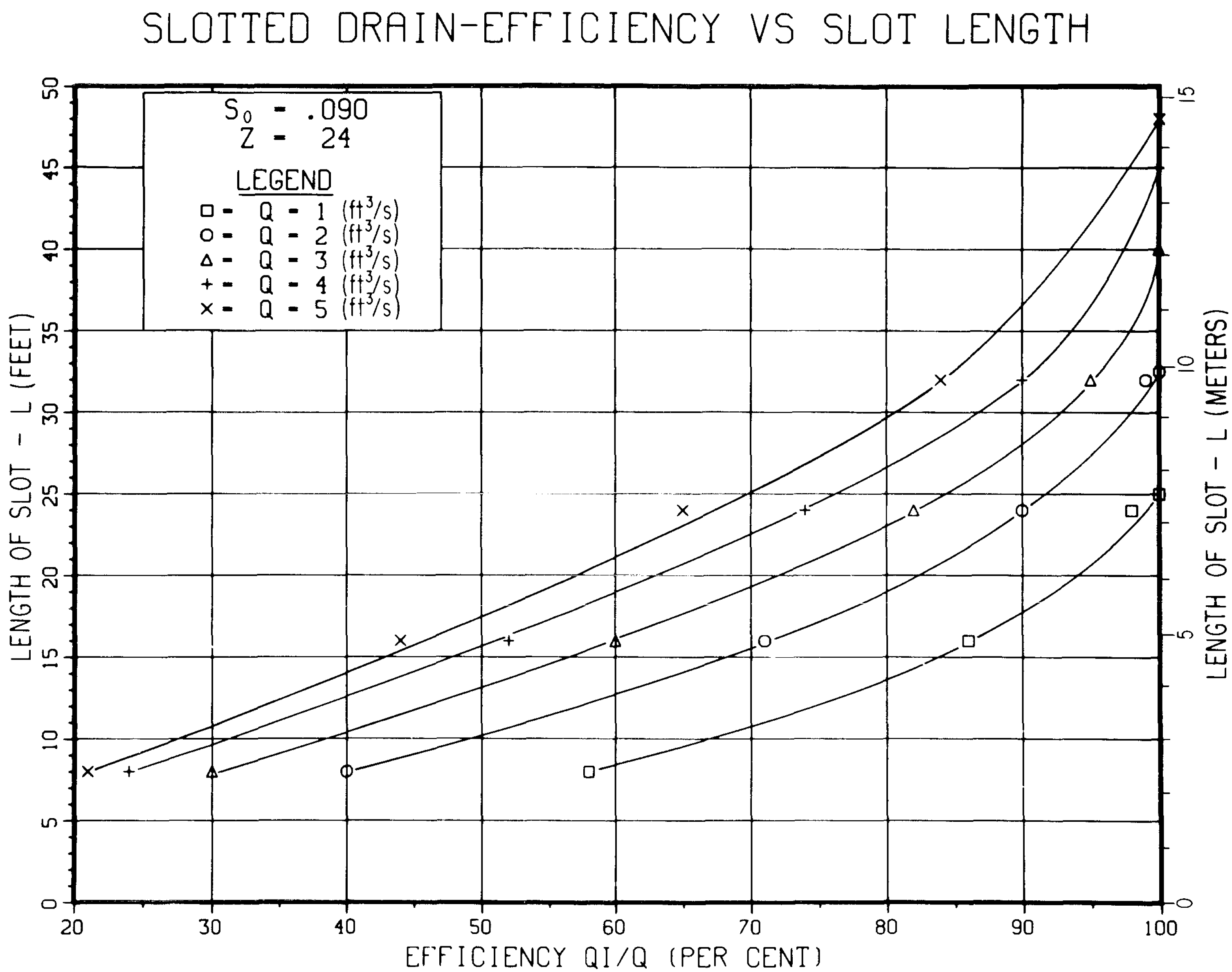


Figure 109. - Efficiency vs. slot length So = 0.09, Z = 24.

SLOTTED DRAIN-EFFICIENCY VS SLOT LENGTH

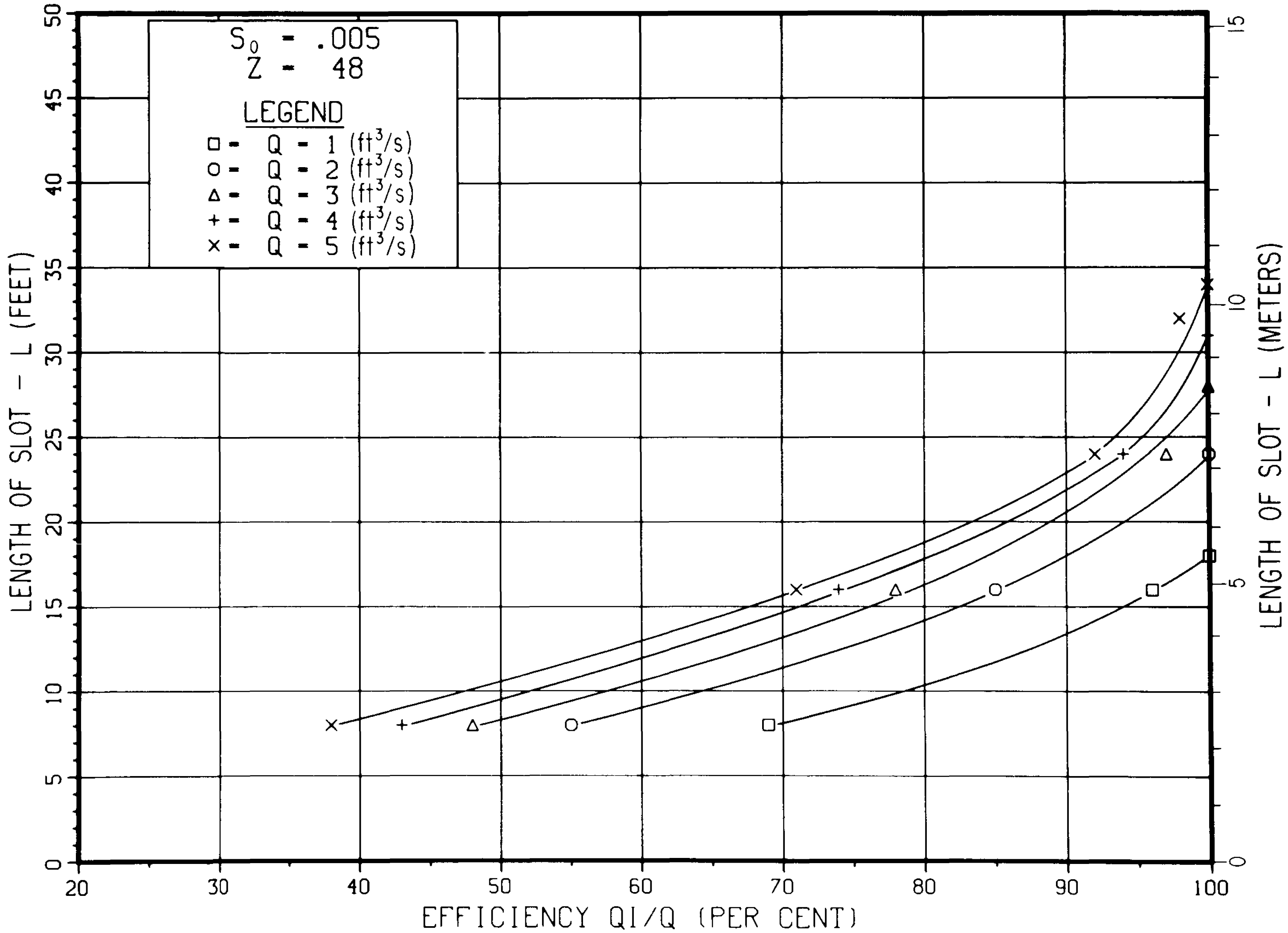


Figure 110. - Efficiency vs. slot length So = 0.005, Z = 48.

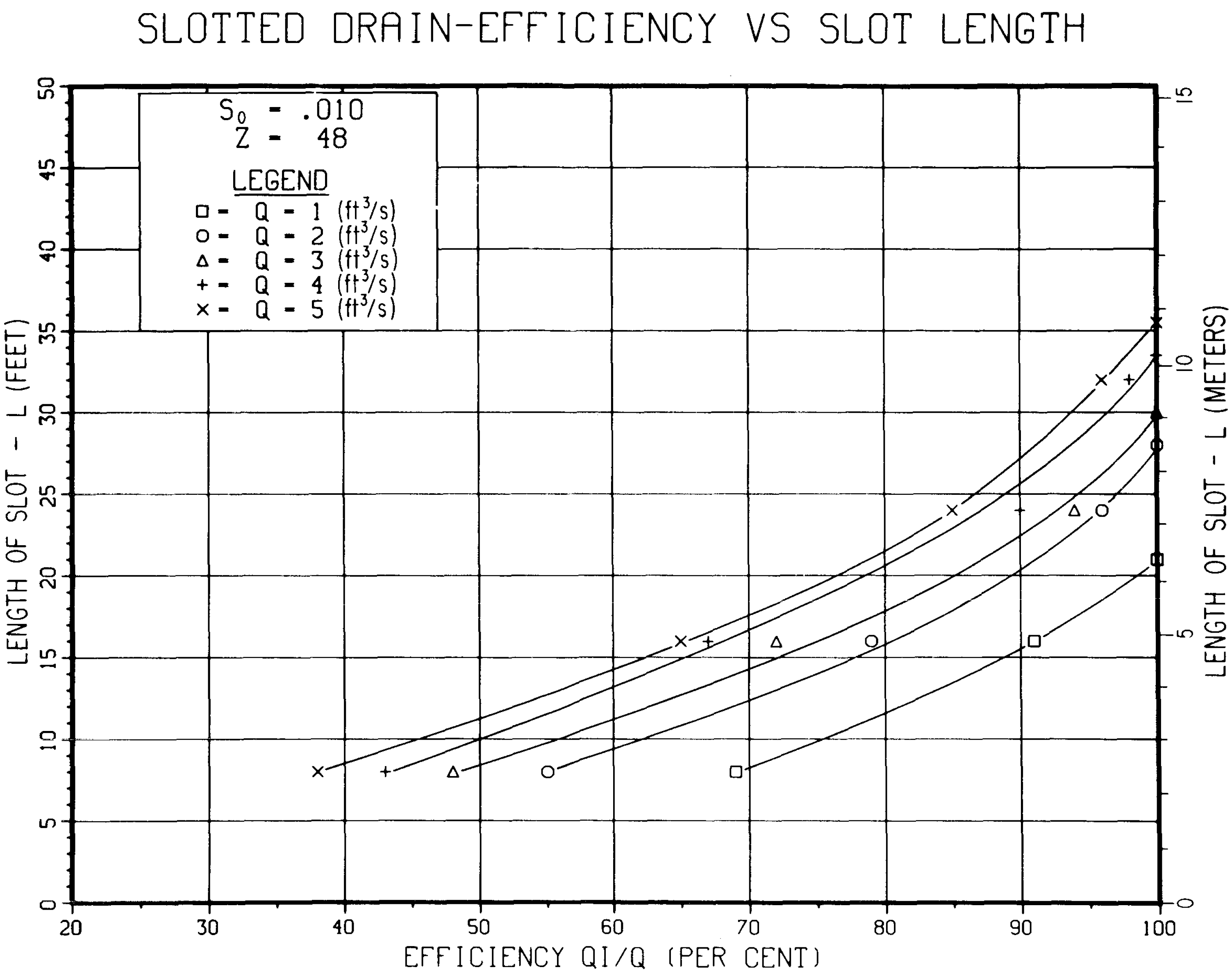


Figure 111. - Efficiency vs. slot length So = 0.01, Z = 48.

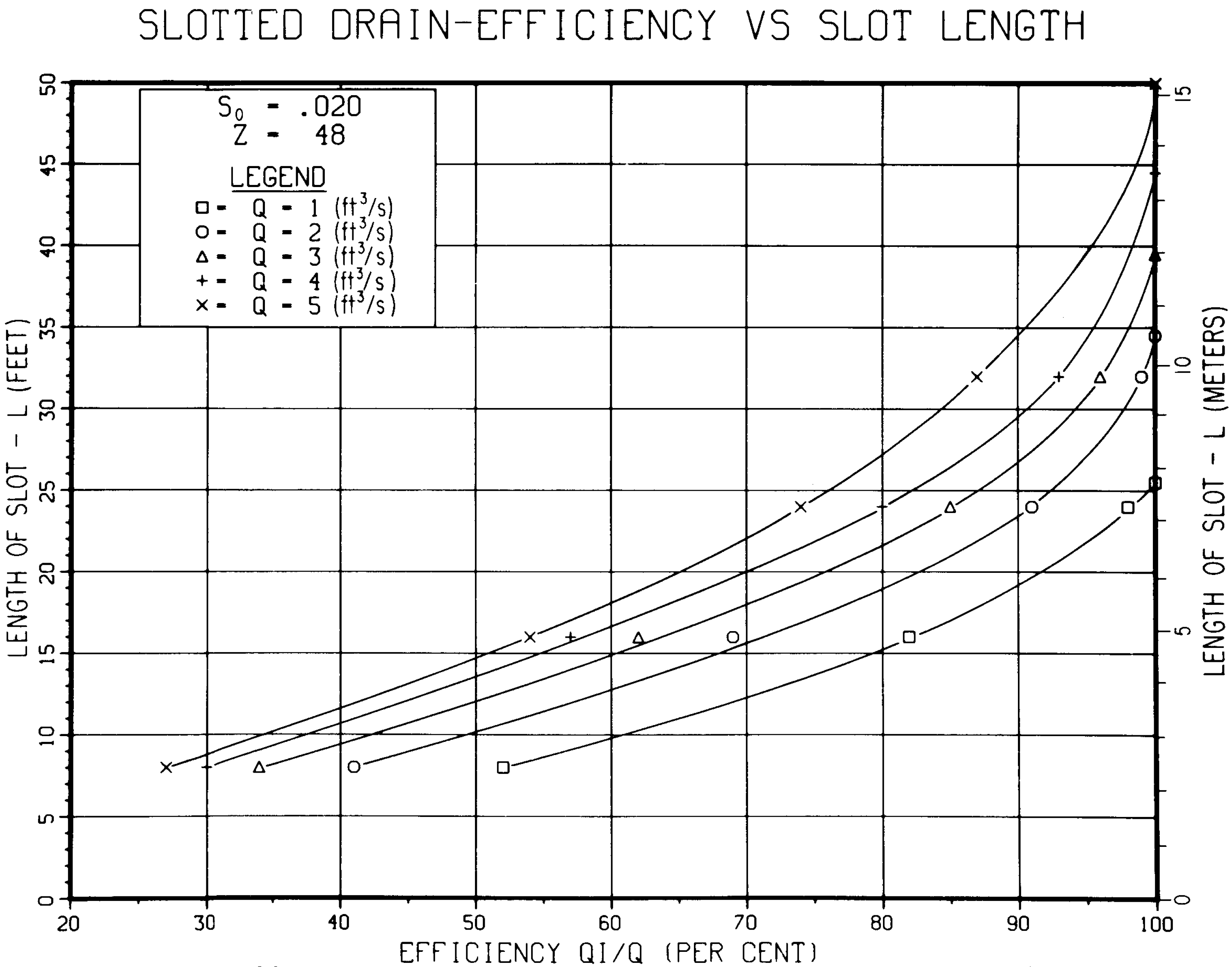


Figure 112. - Efficiency vs. slot length So = 0.02, Z = 48.

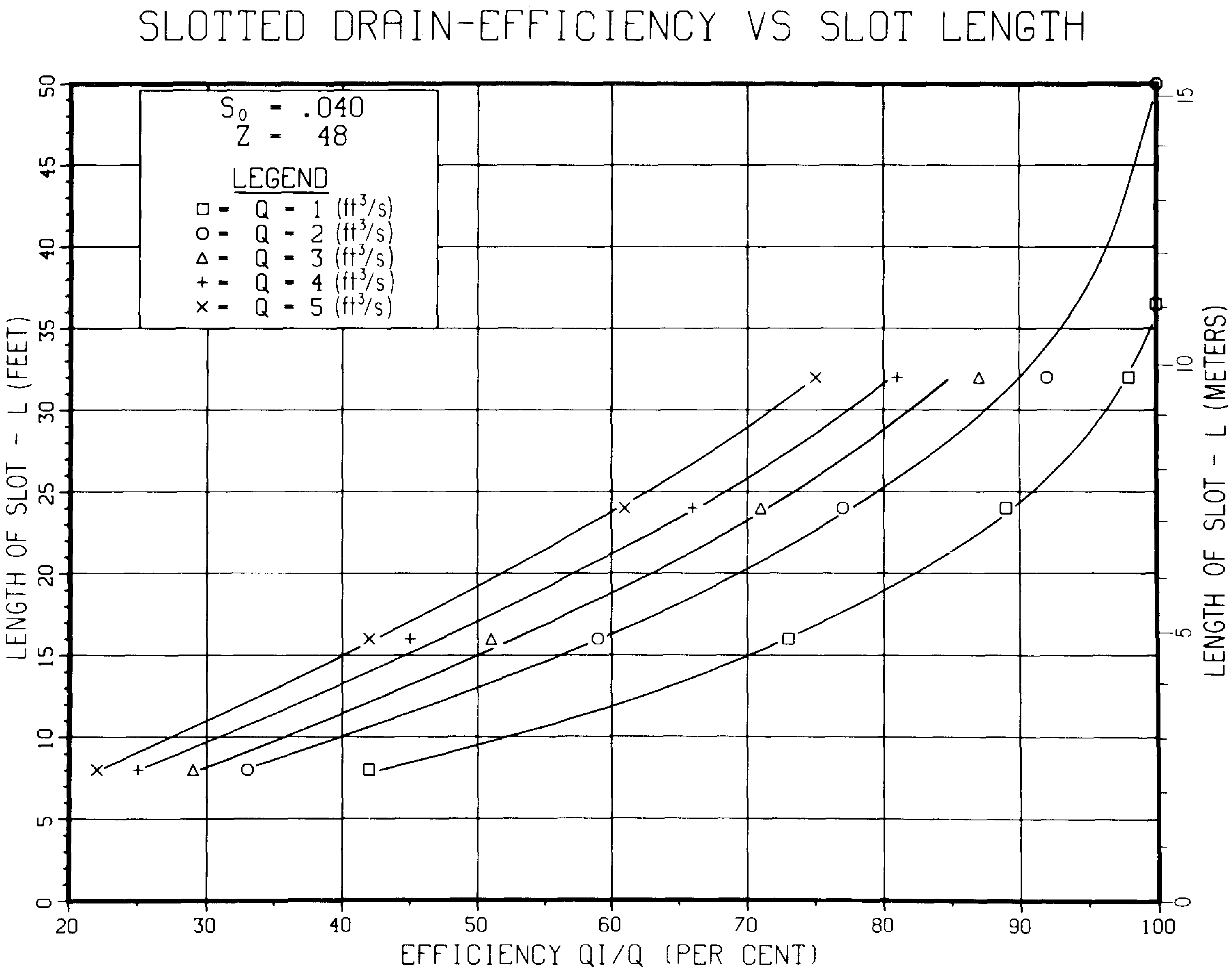


Figure 113. - Efficiency vs. slot length So = 0.04, Z = 48.

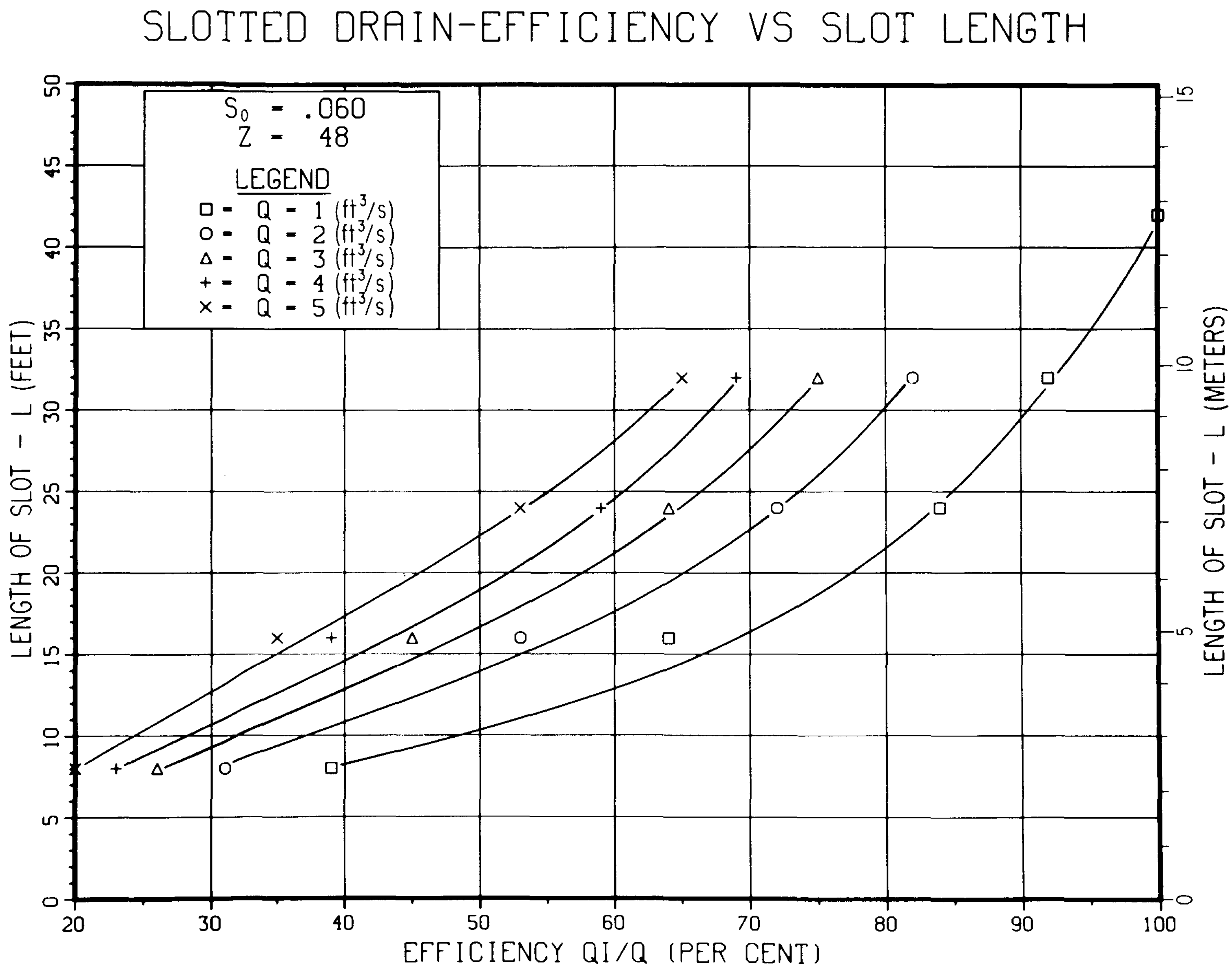


Figure 114. - Efficiency vs. slot length So = 0.06, Z = 48.

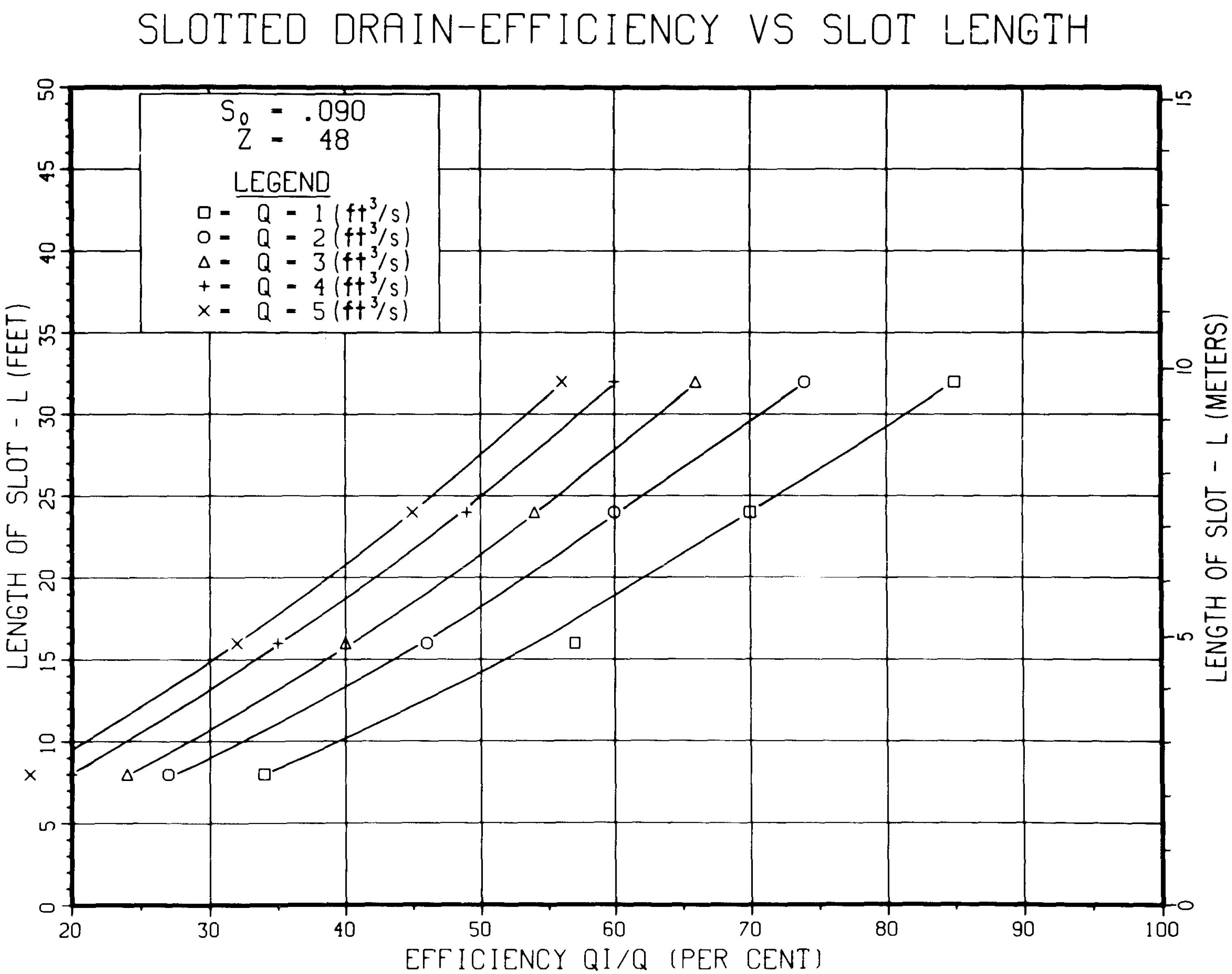
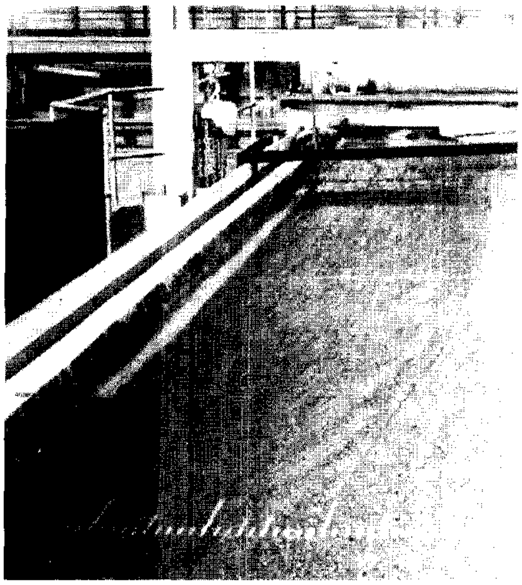
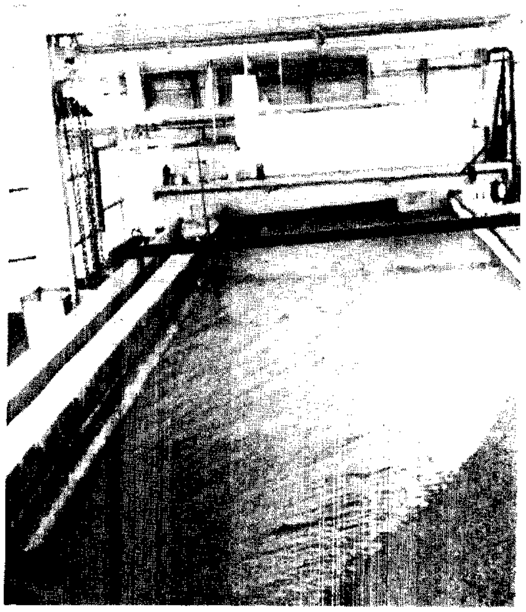


Figure 115. - Efficiency vs. slot length So = 0.09, Z = 48.

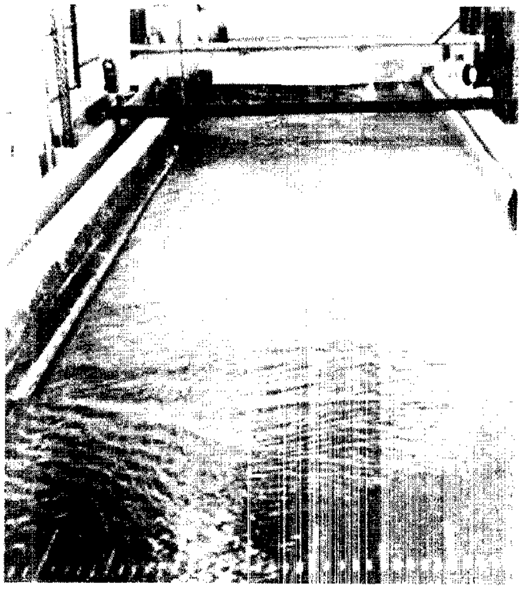


a. $Q = 3.34\ ft^3/s\ (0.095\ m^3/s)$
LA = 16 ft (4.88 m)
E = 68 percent
So = 0.09
Z = 16
L(100 percent) = 30 ft (9.14 m).

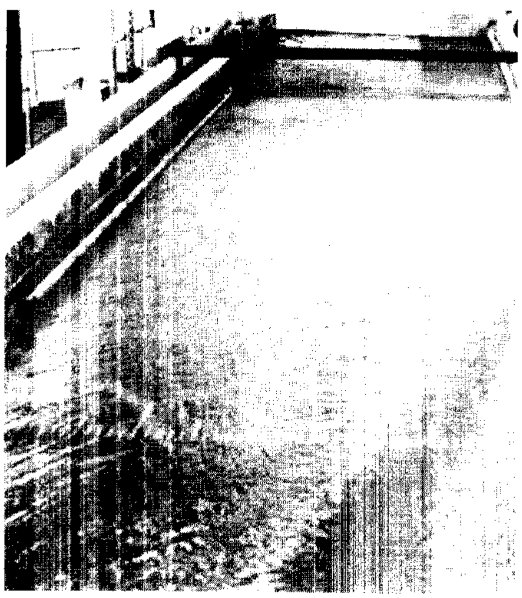


b. $Q = 3.3\ ft^3/s\ (0.093\ m^3/s)$
LA = 16 ft (4.88 m)
E = 90 percent
So = 0.02
Z = 24
L(100 percent) = 23 ft (7.01 m).

Figure 116. - Partial flow capture tests.



a. $Q = 2.18\ ft^3/s\ (0.062\ m^3/s)$
LA = 16 ft (4.88 m)
E = 84 percent
So = 0.005
Z = 48
L(100 percent) = 24 ft (7.32 m).



b. $Q = 1.47\ ft^3/s\ (0.042\ m^3/s)$
LA = 16 ft (4.88 m)
E = 76 percent
So = 0.02
Z = 48
L(100 percent) = 31 ft (9.45 m).

Figure 117. - Partial flow capture tests.

Analysis

Reagan (1) of the Texas Department of Highways and Public Transportation developed a theoretical equation to predict the interception rate of slotted drain inlets. Reagan integrated the weir flow equation (3-3) over a limited length of slot LA, where LA is less than L, resulting in the following equation:

$$LA = (1.645/Cw)(ZSo^{1/2}/n)^{9/16} (Q^{7/16} - Qc^{7/16}) \quad (5\text{-}1)$$

where Q = total discharge
Qc = carryover discharge

Dividing equation 5-1 by equation 3-4 gives the following equation:

$$(LA/L) = 1 - (Qc/Q)^{7/16} \quad (5\text{-}2)$$

If the intercepted flow, Qi = Q-Qc. Equation 5-2 can be written as the ratio of the intercepted flow to the total flow:

$$(Qi/Q) = 1 - (1-LA/L)^{16/7} \quad (5\text{-}3)$$

the hydraulic efficiency of the slot (E) in percent is E = (Qi/Q)100.

Reagan made empirical adjustments to equation 5-3, using experimental data from this study, resulting in the following equation:

$$(E/100) = 1-0.918(1-LA/L)^{1.769} \quad (5\text{-}4)$$

When equation 5-4 was plotted against the observed data, the correlation was good. The total flow capture length, L (in equation 5-4) was computed according to the design procedure described in chapter 3. For E>50 percent, equation 5-4 predicts E within $\pm$ 10 percent and generally within $\pm$ 5 percent. The coefficient of variation at E = 79.2 percent was 7.7 percent, which corresponds to one standard deviation.

Suggested Partial Flow Capture Design Method

For partial flow capture, it is suggested that equation 5-4 be used to determine E for E greater than 50 percent. The total flow capture length should be determined by computing L with equations 3-10 and 3-11 and using the greater of the two values. Any value of LA less than L can be used. This procedure is for SV-1.75-6-3.5 slot installations only. Other slot widths and curb distances will be covered in volume 5.

References

[1] Reagan, J. D., Unpublished Calculations, Texas Department of Highways and Public Transportation, Austin, Texas, March 1978

CHAPTER 6

SLOTTED DRAIN IN A SUMP CONDITION

Introduction

The main purpose of these tests was to determine the discharge through a slot for various water depths and widths of spread. Debris tests were also conducted to determine the relative degree of clogging that can be expected.

In order to get flow depths up to 10-in (254 mm) in a sump condition, a scale model was used. A 1-in (25.4-mm) slot was used, making the scale ratio 1:1.75 for a 1.75-in (44.45-mm) prototype width. The discharge ratio according to the Froude scale relationship was $(1.75)^{5/2}$ = 4.051. Three slot lengths were tested. Model slot lengths of 2.29, 4.57, and 6.86 ft (0.70, 1.39, and 2.09 m) simulated prototype lengths of 4, 8, and 12 ft (1.22, 2.44, and 3.66 m). An 8-in (203.2-mm) high barrier was installed across the roadway about 35 ft (10.67 m) downstream from the headbox. The slot was installed just upstream from the barrier, forcing all the flow through the slot. The roadway was set at a 0.2 percent longitudinal slope and the barrier was assumed to be at the bottom of the sag vertical curve. Measurements included discharge, flow depth, and width of spread at the slot. The discharge was increased until the slot began to be submerged before these tests were started. At lower discharges, the slot performs much the same as a slot installed on a grade. Measurements were made at cross slopes of 1/48, 1/24, and 1/16. Prototype water depths ranged from about 2 in (50.8 mm) to about 10 in (254 mm). Figure 118 contains photographs of several sump tests.

Results

Hydraulic tests. - The discharge coefficient for orifice flow (Co) was computed from the following equation:

$$Co = Q/LW\ (2gy)^{1/2} \qquad (6\text{-}1)$$

where:

- Q = flow (ft^3/s) or (m^3/s)
- L = length of slot (ft) or (m)
- W = width of slot (ft) or (m)
- y = depth of water upstream from the slot (ft) or (m)
- g = gravitational acceleration (ft/s^2) or (m/s^2)

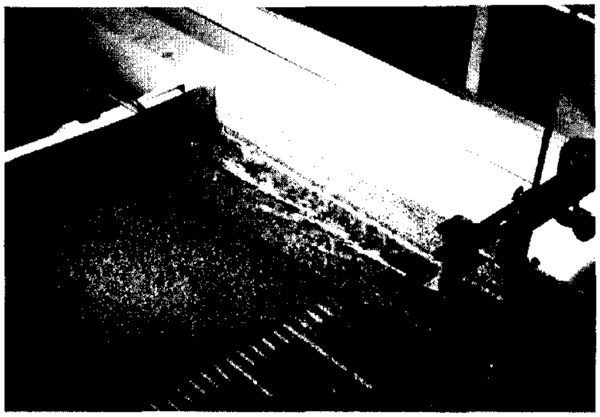
Figure 119 is a plot of discharge coefficient vs. depth. In the transition zone (depth about 0.18 ft, 0.05 m), coefficients are around 0.36. As depth increases, the discharge coefficient increases to about 0.79 on the average at a depth of 0.40 ft (0.12 m). This discharge coefficient is higher than would be expected for a sharp edged orifice (0.61). However, if the slot is considered to be a short tube, the coefficient would be more than 0.61. According to King (1), a standard short tube is a tube with a square-cornered entrance with a length 2-1/2 times its diameter. In the model the entrance width was 1 in (25.4 mm) and the slot depth was 2.50 in (63.75 mm), fitting the definition of a short tube. According to King, the discharge coefficient for a short tube is about 0.82. This explains the high coefficient measured in the model. If the width of the entrance is large compared to the depth of the slot (greater than 1:2.5), the discharge coefficient would be expected to drop to about 0.61. The depth of water was the major factor influencing the discharge. However, the cross slope and slot length had some effect. The discharge coefficient for a particular slot length and flow depth increases as the cross slope is decreased from 1/16 to 1/48. The discharge coefficient is high for shorter slot lengths because the longitudinal velocity component and turbulence are less. The family of curves on figure 119 shows the relationship of cross slope and slot length to discharge coefficient.

Debris tests. - Debris tests were conducted for each slope condition and each slot length. Tests were similar to those described in chapter 3; 150 pieces of 1.71- by 2.29-in (43.4- by 58.2-mm) debris [3- by 4-in, (76.2- by 102.0-mm)] prototype size were scattered on the roadway upstream from the slot. The discharge was then gradually increased for 5 minutes to a point where the model width of spread was about 6.0 ft (1.83 m). This flow was held constant for 5 minutes. The pieces of debris not passing through the slot were then counted. Figure 120 shows photographs of debris tests. Each debris test was repeated three times. Table 4 lists the results of the debris tests.

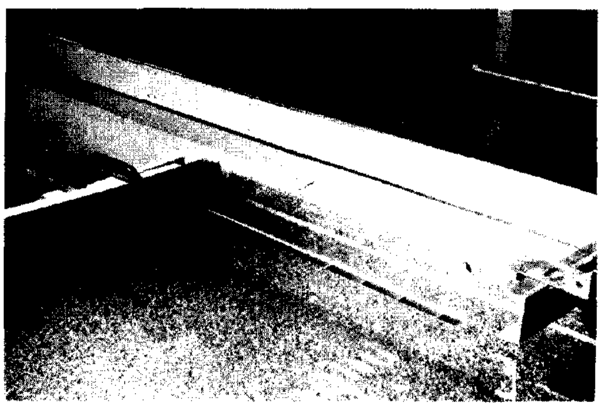
These data indicated that as the slot length is increased and the cross slope is increased, the debris efficiency increases. As expected, the slot is more efficient for steeper cross slopes because the water is deeper at the slot and more pieces of debris are washed through. The longer slots are more efficient because there are fewer pieces of debris per unit length of slot and most of the debris accumulates at the bottom of a sag vertical curve.

References

[1] King, Wisler, Wooddyn, "Hydraulics," Fifth Edition, John Wiley and Sons, Inc., pp. 140-141

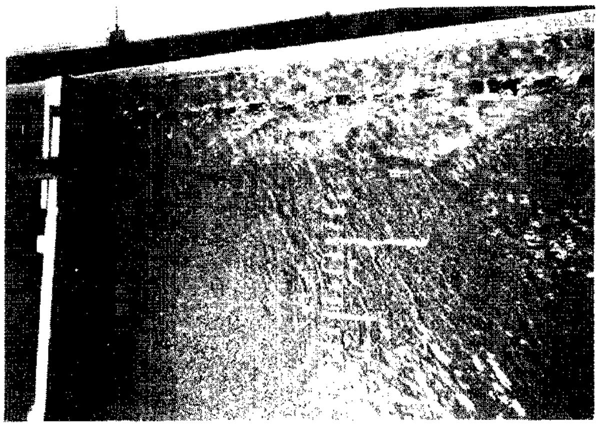


a. $Q = 0.506\ ft^3/s\ (0.014\ m^3/s)$
$L = 2.29$ ft (0.698 m)
$T = 4.7$ ft (1.433 m)
$Y = 0.19$ ft (0.058 m)
$Z = 16$

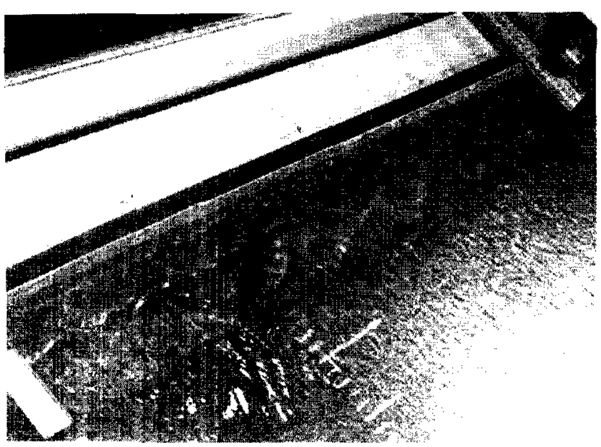


b. $Q = 0.820\ ft^3/s\ (0.023\ m^3/s)$
$L = 2.29$ ft (0.698 m)
$Y = 0.488$ ft (0.149 m)
$Z = 16$

Figure 118. - Sump tests (dimensions and amounts given in model scale).



c. Q = 1.00 ft^3/s (0.028 m^3/s)
L = 4.57 ft (1.393 m)
T = 4.0 ft (1.219 m)cent
Y = 0.202 ft (0.062 m)
Z = 16



d. Q = 1.83 ft^3/s (0.052 m^3/s)
L = 6.86 ft (2.091 m)
T = 5.3 ft (1.615 m)
Y = 0.280 ft (0.085 m)
Z = 16

Figure 118. - Continued

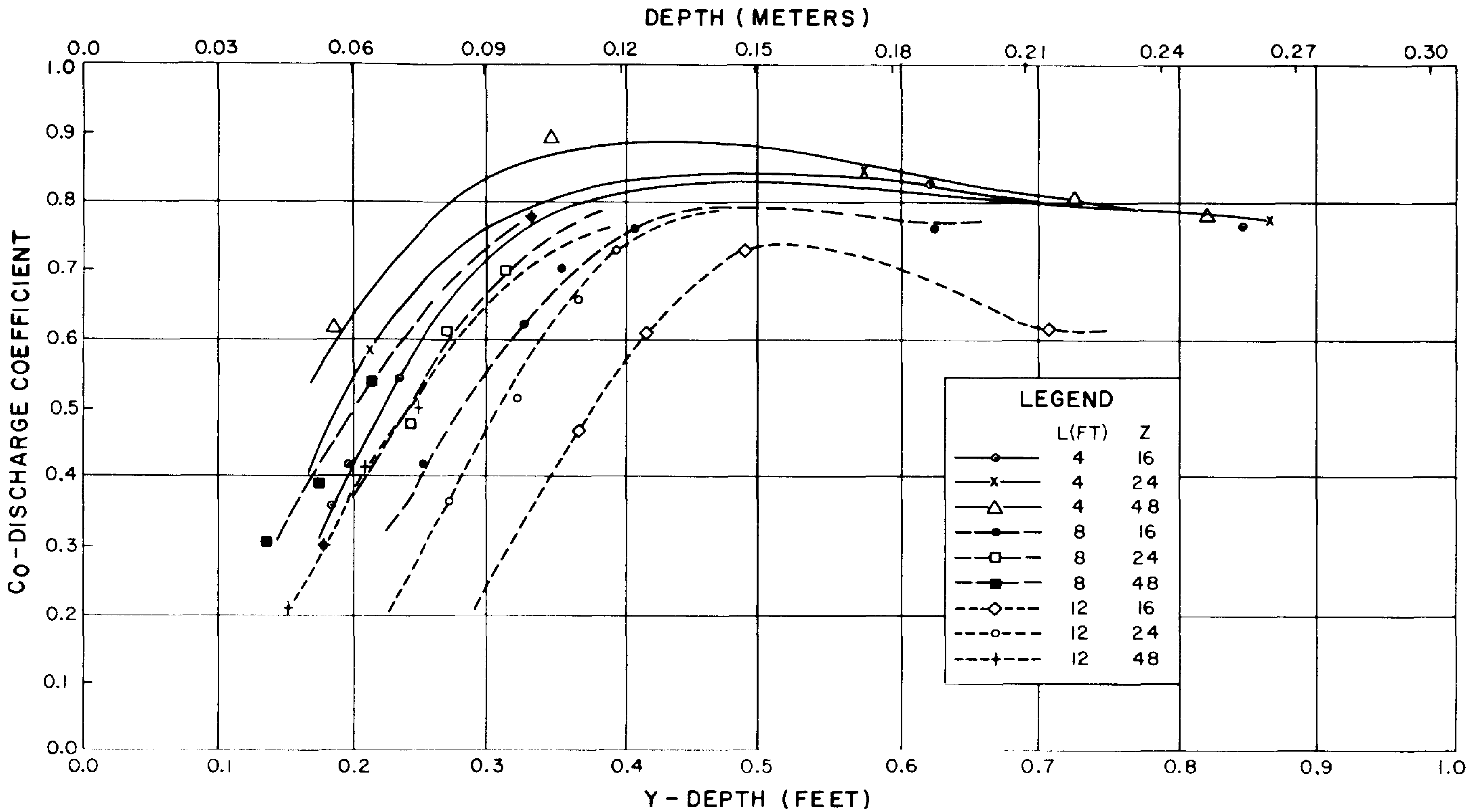
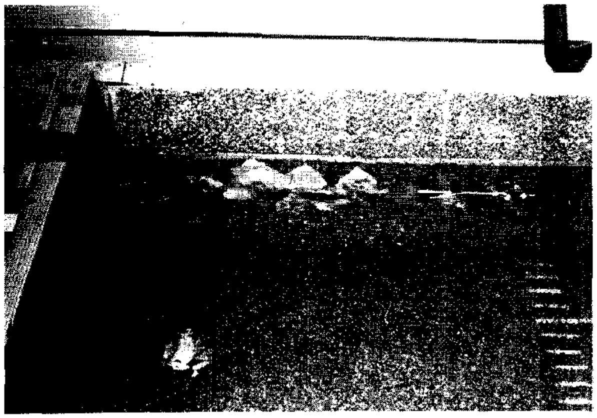
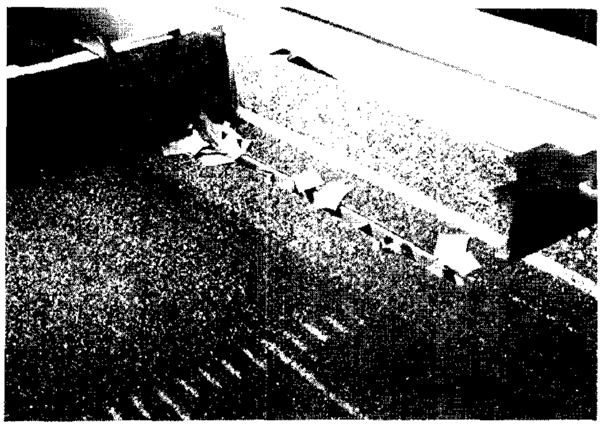


Figure 119. - Discharge coefficient (Co) vs. depth in a sump slot installation (1 foot = 0.305 m).

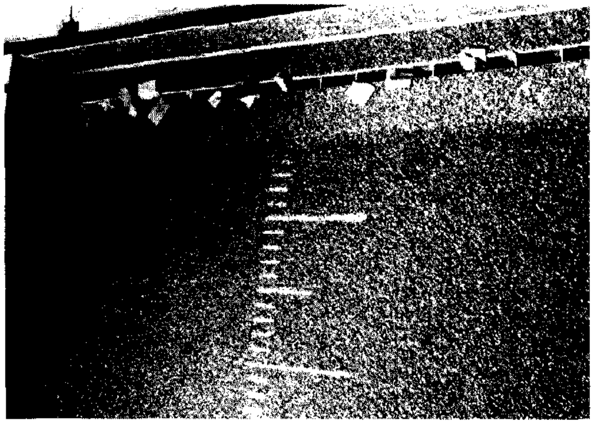


a. L = 2.29 ft (0.698 m)
$\overline{E}$ = 38 percent
Z = 48

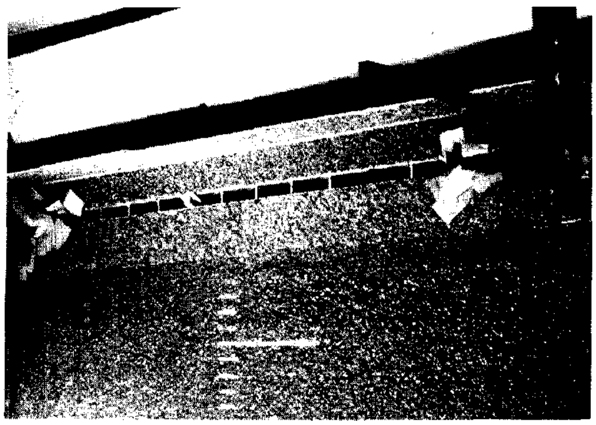


b. L = 2.29 ft (0.698 m)
$\overline{E}$ = 70 percent
Z = 16

Figure 120. - Sump condition debris tests (model dimensions given).



c. $\underline{L}$ = 4.57 ft (1.393 m)
$\overline{E}$ = 76 percent
Z = 16



d. $\underline{L}$ = 4.57 ft (1.393 m)
$\overline{E}$ = 54 percent
Z = 48

Figure 120. - Continued.

Table 4. - Average debris efficiency* - (%)
slotted drain in a sump condition

Length	S_x = 1/16	S_x = 1/24	S_x = 1/48
4 ft	70	57	38
8 ft	76	71	54
12 ft	81	73	81

* ($\overline{E}$) - Each value is the percentage of 150 - 3- by 4-in pieces of debris passing through a slot in a sump condition (0.3048 m = 1 ft).

CHAPTER 7

SUMMARY

Tests were conducted to study the effect of individual parameters on efficiency of slotted drains. The parameters studied included:

1. Total flow interception capacity for different:
   a. Roadway roughnesses
   b. Transverse bar spacings and designs
   c. Slot widths
   d. Distances from curb to slot
   e. Combinations of sheet flow and gutter flow
2. Partial flow interception capacity
3. Sheet flow interception capacity
4. Interception capacity of slot in a sump condition
5. Debris handling ability

The following points summarize the test results:

1. In most field conditions, weir flow controls the total flow capture length (L). The type of transverse bar and slot width has little effect on L in the weir flow zone. For an SV-1.75-6-3.5 slot installation, the following equation accurately predicts L when weir flow is controlling:

$$L = 0.706\ Q^{0.442}\ So^{A}\ Z^{0.849}/n^{0.385} \qquad (3\text{-}10)$$

where:

$$A = 0.207 + 0.007\ Z + 2.613\ So - 0.049\ So\ Z - 19.084\ So^2 - 0.0001\ Z^2 \qquad (3\text{-}9)$$

Table 3 gives typical values of A.

2. An inefficient type of submerged flow increases L for some slot installations at steep slopes. The point where this submerged flow condition starts controlling L is dependent on the roadway roughness, slot width, type of transverse bar, slope conditions, and curb distance. For a SV-1.75-6-3.5 slot installation, the following equation predicts L accurately in the submerged flow region:

$$L = 0.394\ Q^{0.649}\ So^{0.410}\ Z^{0.450}/n^{0.811} \qquad (3\text{-}11)$$

3. Slotted drain is a more efficient flow interceptor in the upstream portion of the slot. About 70 percent of the flow is captured in 46 percent of the length required to capture all the flow (for a SV-1.75-6-3.5 slot installation). The following equation can be used to determine how much flow will be intercepted for a given length of slot (LA):

$$(E/100) = 1 - 0.918\ (1\text{-}LA/L)^{1.769} \qquad (5\text{-}4)$$

4. Transverse bar spacing has the most effect on debris handling capability of the slot. Transverse bars at 4-in (101.6-mm) centers are considerably less efficient at passing debris than bars with 6-in (152.4-mm) centers. Wider slots are more efficient than narrow slots. Short slots in a sump condition are more likely to clog up with debris since most of the debris accumulates near the bottom of a sag vertical curve or the front of the slot.

5. Slotted drains are capable of intercepting a large sheet flow. The narrowest slot tested (1 in, 25.4 mm) intercepted essentially all sheet flow, up to the system capacity of 0.040 ft^3/s per ft (0.345 l/s per m).

6. The orifice equation can be used to determine the flow capacity of slots in a completely submerged sump condition:

$$Q = Co\ LW\ (2gy)^{1/2} \qquad (6\text{-}1)$$

The orifice flow discharge coefficient (Co) was found to be 0.79 at depth above 0.40 ft (0. 12 m).

7. Introducing a portion of the flow as sheet flow has essentially no effect on the 100 percent flow capture length. Therefore, the data in figures 61, 62, and 63 supplement the data set for a SV-1.75-6-3.5 slot installation.

☆ U. S. GOVERNMENT PRINTING OFFICE : 1980

FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.*

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

* The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.