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BICYCLE-SAFE GRATE INLETS STUDY

Vol. 2 Hydraulic Characteristics of Three Selected Grate Inlets on Continuous Grades

May 1978

Final Report

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Offices of Research & Development

Washington, D. C. 20590

Foreword

This report describes the additional hydraulic tests conducted on three selected grate inlet designs identified in Volume 1 as possessing best overall qualities on bicycle-safety, hydraulic efficiency and debris handling characteristics. From the results of this report, together with those presented in Volume 1 (FHWA-RD-77-24), hydraulic efficiencies can be estimated for these three grates of any size within the widths of 15 in. to 36 in. (0.38 m to 0.91 m) and lengths of 24 in. to 48 in. (0.61 m to 1.22 m).

This research is being 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 results of tests on these three grates at the low point of a sag vertical curve (or the so-called "sump condition") and on the slotted drain design.

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16. ABSTRACT

Additional hydraulic tests were conducted on three grate inlet designs identified as bicycle safe, hydraulically efficient and having good debris handling characteristics. The grates were selected based on the results of a previous study - Bicycle-safe Grate Inlets Study - Volume I Hydraulic and Safety Characteristics of Selected Grate Inlets on Continuous Grades. The major objective of the initial study was to identify, develop, and analyze selected grate inlets which maximize hydraulic efficiency and bicycle safety.

Full size grates in sizes of 3.0 ft by 4.0 ft (0.91 m by 1.22 m), 3.0 ft by 2.0 ft (0.91 m by 0.61 m), 1.25 ft by 2.67 ft (0.38 m by 0.81 m), and 1.25 ft by 2.0 ft (0.38 m by 0.61 m) were tested at cross slopes of 1:48, 1:24, and 1:16 and longitudinal slopes of 0.5, 1.0, 2.0, 4.0, 6.0, 9.0, and 13 percent with gutter flows up to 5.6 ft^3/s (0.159 m^3/s). Numerous design curves are provided to aid the hydraulic design engineers with grate inlet selection.

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SUMMARY

Additional tests were conducted with three grate inlet designs that were selected as bicycle and pedestrian safe as well as hydraulically efficient in volume 1 of this series - Bicycle Safe Grate Inlets Study. The purpose of these additional tests was to broaden the available design data for grate inlet widths from the 2 ft (0.61 m) width of volume 1 to include widths of 1.25 ft (0.38 m) and 3.0 ft (0.91 m). Four full scale grate inlet sizes were tested. They included: 1.25 ft by 2.0 ft (0.38 m by 0.61 m), 1.25 ft by 2.67 ft (0.38 m by 0.81 m), 3.0 ft by 2.0 ft (0.91 m by 0.61 m), and 3.0 ft by 4.0 ft (0.91 m by 1.22 m).

The three grate inlet designs tested included a parallel bar grate with a 3/4 in (19 mm) clear spacing between bars, a parallel bar grate with transverse rods on 4 in (102 mm) centers at the surface, and a cast grate with transverse curved vane bearing bars. Hydraulic efficiency tests were conducted at cross slopes of 1/48, 1/24, and 1/16 and longitudinal slopes of 0.5, 1.0, 2.0, 4.0, 6.0, 9.0, and 13.0 percent with gutter flows up to 5.6 ft^3/s (0.158 m^3/s).

In general for the higher energy gutter flow conditions the P - 1-1/8 and CV - 3-1/4 - 4-1/4 grate inlets were more efficient than the P - 1-7/8 - 4. For low energy gutter flow conditions, the CV - 3-1/4 - 4-1/4 grate inlet was normally somewhat less efficient than the fabricated steel grates.

ACKNOWLEDGEMENTS

This study was conducted by the U.S. Bureau of Reclamation (USBR) 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 for their contribution in selected areas of the study:

1. Hydraulic tests - Douglas Gober, James Francisco, Theresa Satchell, Gary Rome, Pete Julius
2. Drafting - Joseph Santillana
3. Photography - W. M. Batts

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The contract was monitored by Dr. D. C. Woo, Contract Manager, Environmental Design and Control Division, Federal Highway Administration.

NOTATION

E = hydraulic efficiency

Q_I = flow intercepted by grate

Q_T = gutter flow

S_0 = longitudinal slope

T = calculated width of spread

T' = measured width of spread

y = depth of flow at the curb

Z = reciprocal of the cross slope, T/y

CHAPTER 1

INTRODUCTION

This volume presents the results of additional hydraulic tests conducted on three bicycle safe grate inlets identified in volume 1. The objective of the original study was to identify, develop, and analyze selected grate inlets which maximize hydraulic efficiency and bicycle safety. As a result of the original study, three of the eight grates tested were identified as superior in performance, using the criteria of bicycle safety, hydraulic efficiency, and debris handling ability.

The three grates included (1) a parallel bar grate with 3/4 in (19 mm) spacers (smaller than the 7/8 in (22 mm) narrowest bicycle tires), designated the P - 1-1/8, because the center-to-center spacing of the parallel bars is 1-1/8 in (28.6 mm); (2) a parallel bar grate with a 1-7/8 in (47.6 mm) center-to-center spacing of the parallel bars, and transverse rods spaced 4 in (102 mm) on centers called a P - 1-7/8 - 4; and (3) a curved vane grate, designated CV - 3-1/4 - 4-1/4, because the longitudinal bars are spaced 3-1/4 in (82.6 mm) center-to-center and the transverse curved vane members spaced at a nominal 4-1/4 in (108 mm).

The hydraulic efficiency tests were conducted on the same hydraulic test facility described in volume 1. The additional tests were conducted on four grate sizes, 1.25 ft by 2.0 ft (0.38 m by 0.61 m), 1.25 ft by 2.67 ft (0.38 m by 0.81 m), 3.0 ft by 2.0 ft (0.91 m by 0.61 m), and 3.0 ft by 4.0 ft (0.91 m by 1.22 m). As in the previous tests, using 2.0 ft by 2.0 ft (0.61 m by 0.61 m) and 2.0 ft by 4.0 ft (0.61 m by 1.22 m) grate sizes, the grate inlets were tested at cross slopes of 1/48, 1/24, and 1/16 and longitudinal slopes of 0.5, 1.0, 2.0, 4.0, 6.0, 9.0, and 13.0 percent.

The analysis of bicycle and pedestrian safety was presented in chapter 3 of volume 1. Details of experimental equipment and test procedures were covered in chapter 5 of volume 1.

Grate inlet capacity curves were developed for the four grate sizes tested and can be used to determine hydraulic efficiency, E, for intercepted flow, Q_I, for various combinations of gutter flow, Q_T, longitudinal, and cross slopes, S_0, and 1/Z. The structural and hydraulic analyses of each grate inlet design are summarized in the individual chapters and in the Discussion of Results and Conclusions chapter of this volume.

CHAPTER 2

THE PARALLEL BAR GRATE WITH SPACERS - P - 1-1/8

This chapter contains the results of additional hydraulic tests conducted on parallel bar grates with a 3/4 in (19 mm) clear spacing between 3/8 in (9.5 mm) wide longitudinal bars. Since the longitudinal bars are on 1-1/8 in (28.6 mm) centers, this grate will be referred to as the P - 1-1/8 grate (chapter 12, vol. 1). There is no need for transverse bars with this grate since the close spacing prohibits the narrowest of bicycle tires from falling between the longitudinal bars. Spacer bars and 1/2 in (13 mm) pipe 3/4 in (19 mm) wide are used to maintain the 3/4 in (19 mm) space along the length of the grate. The four P - 1-1/8 grate sizes tested are illustrated in figure 2-1. Table 2-1 summarizes the required depth of bearing bars for the four grate inlet sizes. Chapter 2 of vol. 1 describes the analytical approach used to determine bearing bar size. A simple beam analysis was used for all sizes of the P - 1-1/8 grate inlet.

Hydraulics

The hydraulic test results for the P - 1-1/8 grates are shown in figures 2-2 through 2-5. For a specific gutter flow, Q_T, the steeper cross slopes, 1/Z, result in higher hydraulic efficiencies. For both the 1.25 ft and 3 ft (0.32 m and 0.91 m) wide grates, the longer lengths of grates are more efficient for the same test conditions.

The grate width has more impact on hydraulic efficiency than grate length since the major portion of the intercepted flow enters the grate from the upstream end of the grate inlet. As further evidence, one can compare figure 2-3 of this volume with figure 12-2, volume 1. The 3 ft by 2 ft (0.91 m by 0.61 m) grate in figure 2-3 has a surface area of 6 ft^2 (0.56 m^2). The 2 ft by 4 ft (0.61 m by 1.22 m) grate in figure 12-2 of volume 1 has a surface area of 8 ft^2 (0.74 m^2), a third greater than the 3 ft by 2 ft (0.91 m by 0.61 m) grate. In general, the 3 ft by 2 ft (0.91 m by 0.61 m) grate is considerably more efficient than the larger 2 ft by 4 ft (0.61 m by 1.22 m) grate. This results from the greater portion of cross-sectional flow area intercepted by the 3 ft (0.91 m) wide grate compared to that intercepted by the 2 ft (0.61 m) wide grate.

Although there is relatively little splash resulting from the P - 1-1/8 design, figure 2-6a, shorter lengths of the grate will result in severe splash, figure 2-6b. Table 2-2 identifies the maximum efficiency slopes, S_0, for given lengths of the P - 1-1/8 grate under specific cross slope conditions.

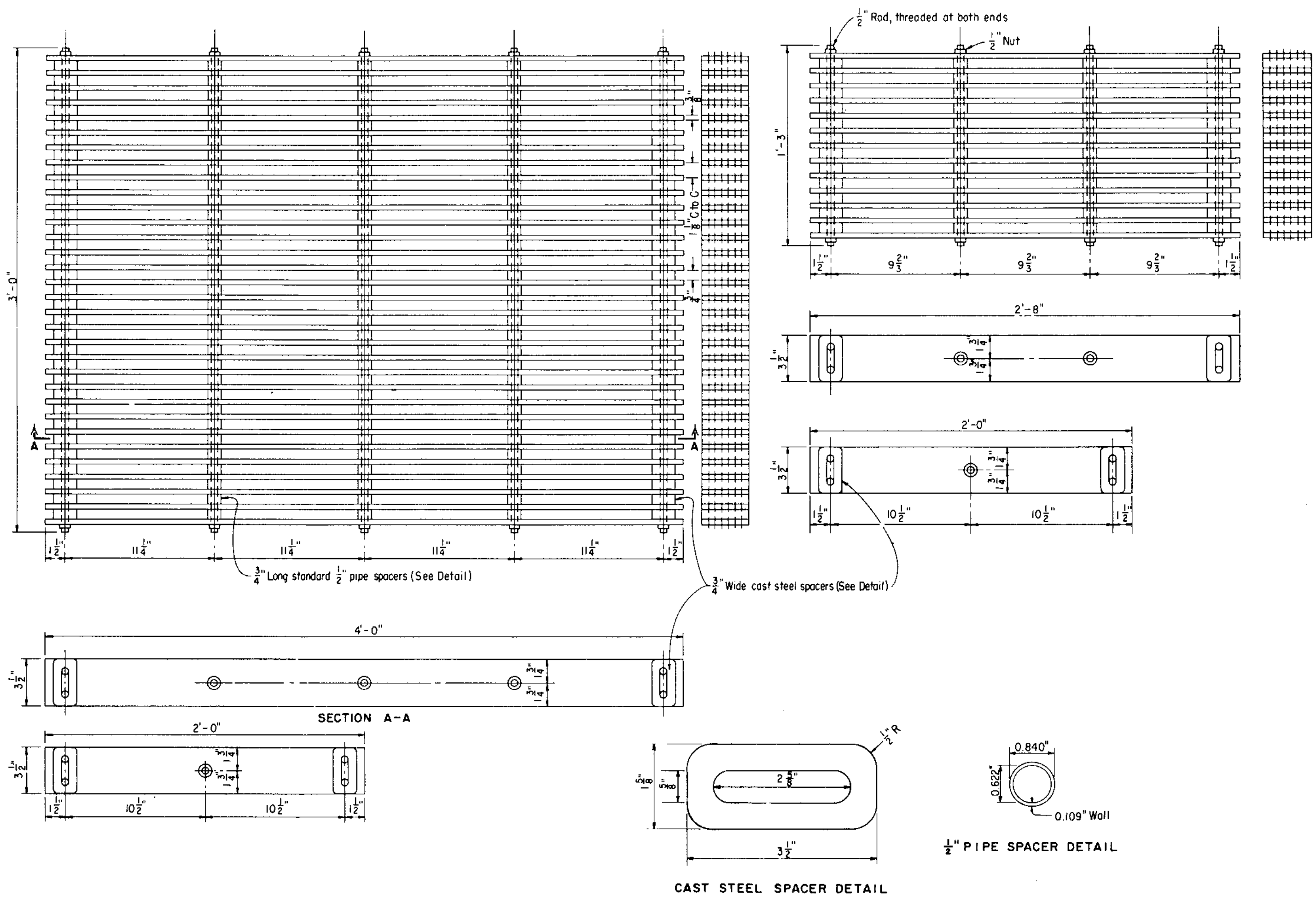


Figure 2-1. - Fabricated steel P - 1-1/8 grate.

Table 2-1. - *Required depth of bearing bars for P - 1-1/8 grates*

Bar thickness		3.0 by 4.0 ft (0.91 by 1.22 m) Span (S) = 3.88 ft (1.18 m)		3.0 by 2.0 ft (0.91 by 0.61 m) S = 1.88 ft (0.57 m)		1.25 by 2.67 ft (0.38 by 0.81 m) S = 2.54 ft (0.77 m)		1.25 by 2.0 ft (0.38 by 0.61 m) S = 1.88 ft (0.57 m)	
in	(mm)	in	(mm)	in	(mm)	in	(mm)	in	(mm)
0.50	(12.70)	3.06	(77.7)	2.00	(50.8)	2.41	(61.2)	2.00	(50.8)
0.375	(9.53)	3.30	(83.8)	2.16	(54.9)	2.60	(66.0)	2.16	(54.9)
0.25	(6.35)	3.82	(97.0)	2.50	(63.5)	3.00	(76.2)	2.50	(63.5)

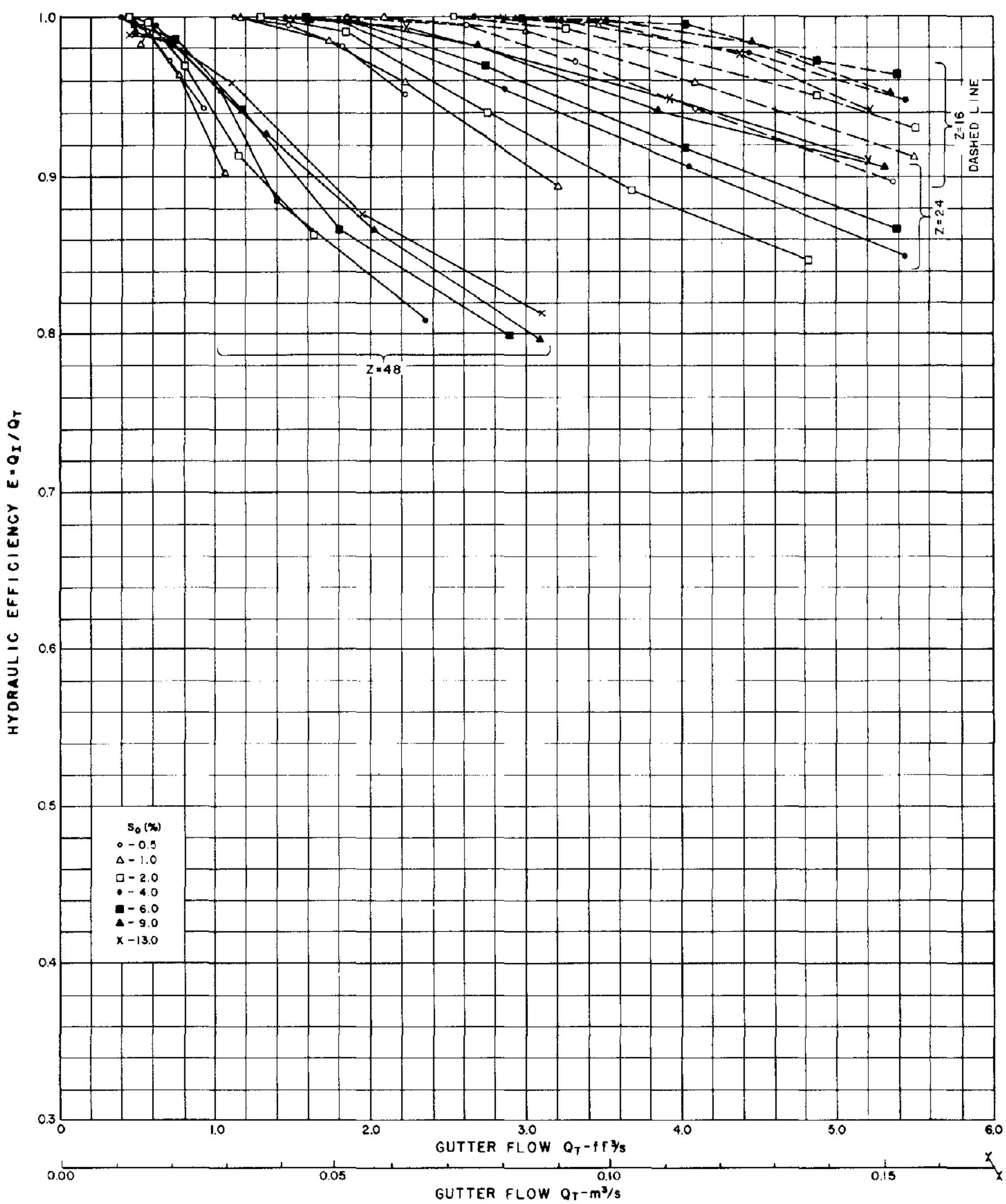


Figure 2-2. - Hydraulic efficiency vs. gutter flow, 3.0 ft by 4.0 ft (0.91 m by 1.22 m) P - 1-1/8 grate.

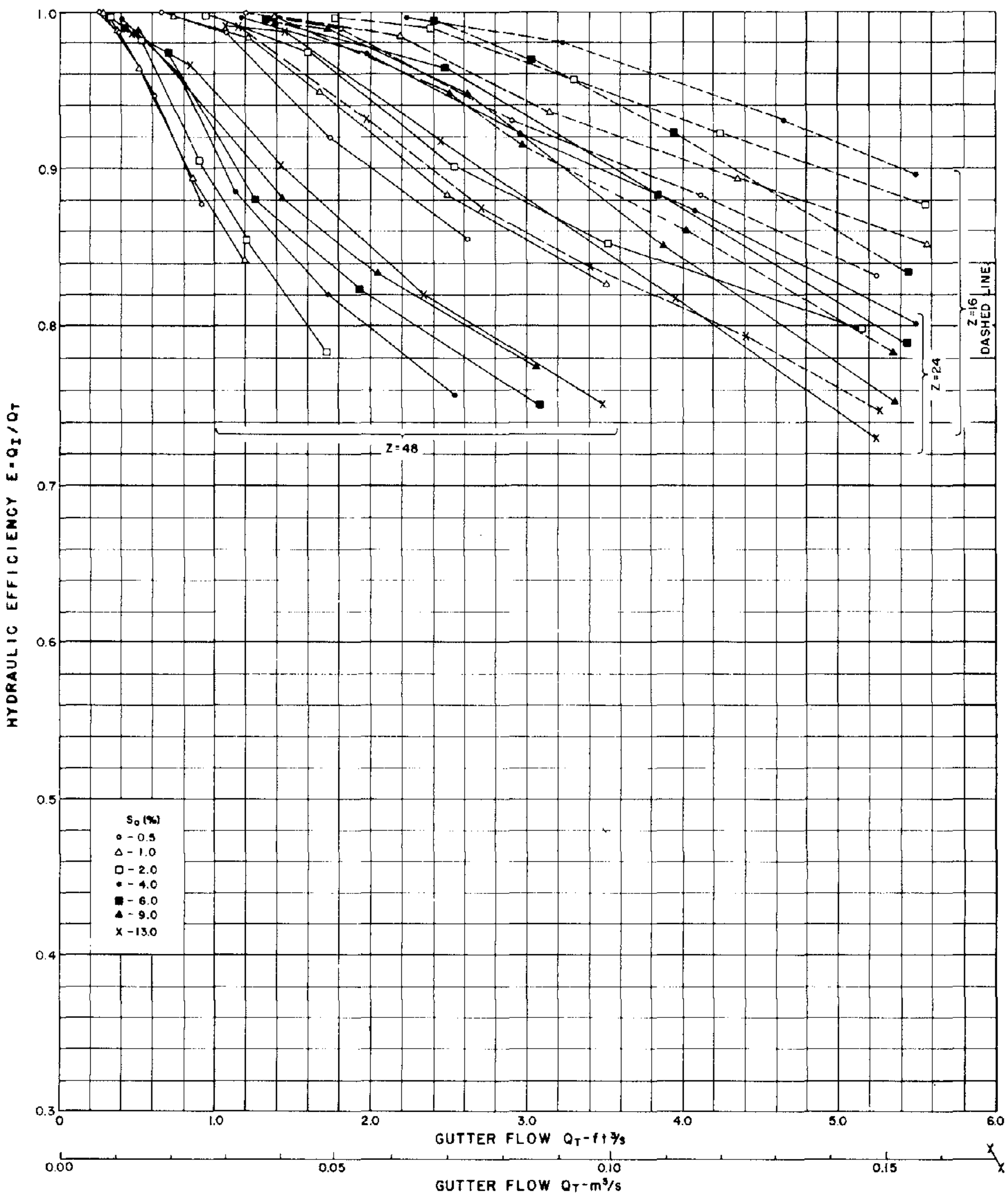


Figure 2-3. - Hydraulic efficiency vs. gutter flow, 3.0 ft by 2.0 ft (0.91 m by 0.61 m) P - 1-1/8 grate.

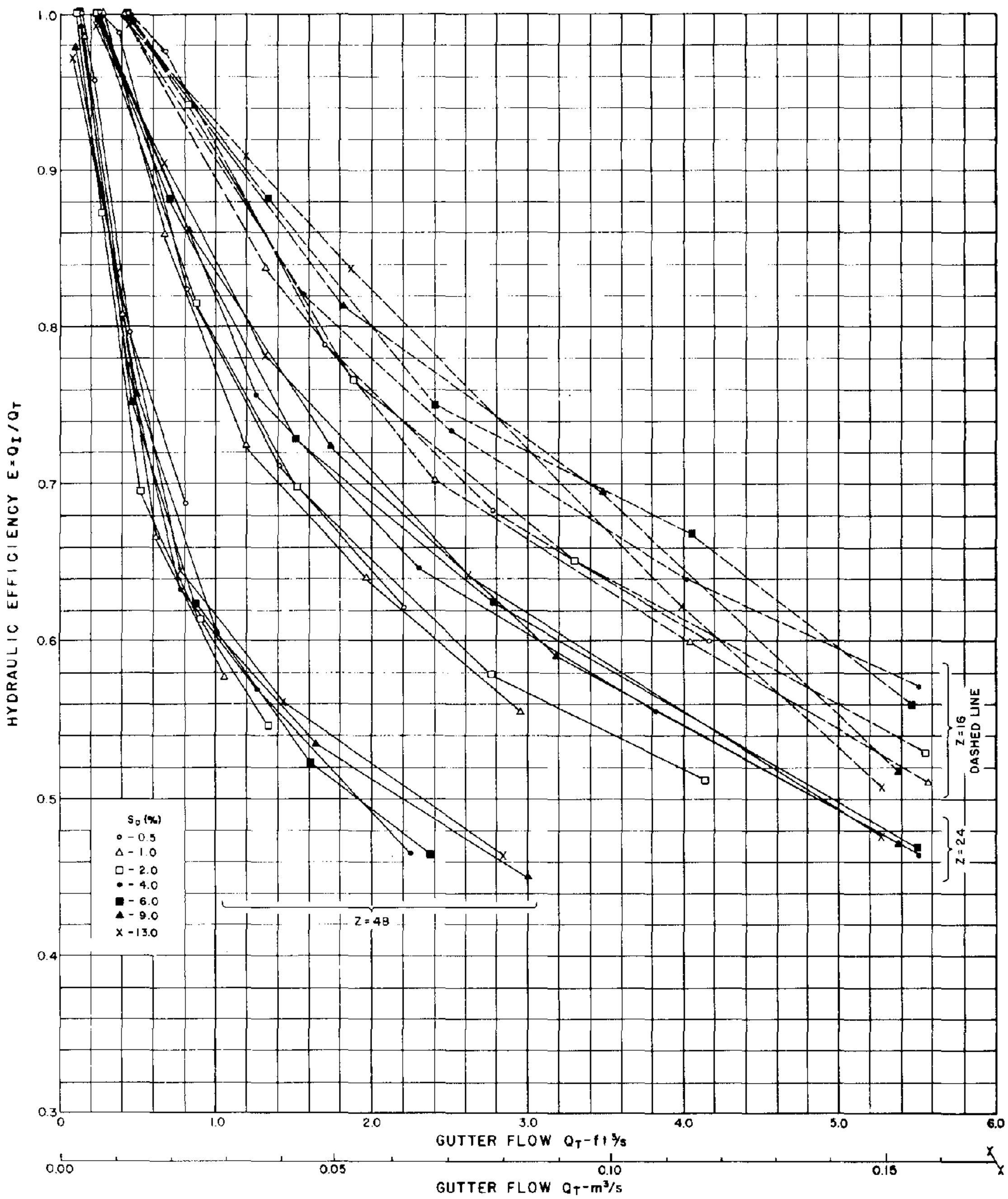


Figure 2-4. - Hydraulic efficiency vs. gutter flow,
1.25 ft by 2.67 ft (0.38 m by 0.81 m)
P - 1-1/8 grate.

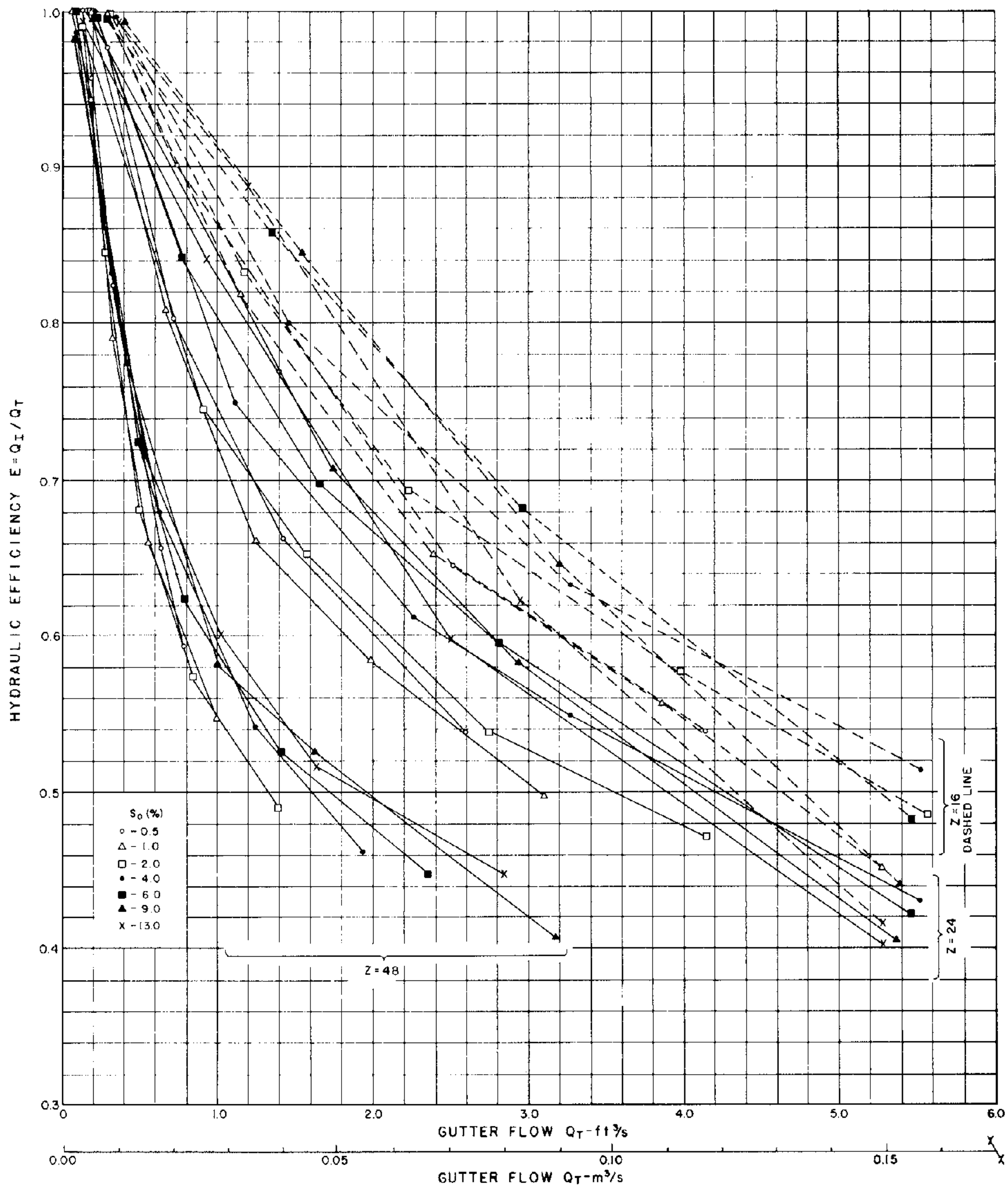
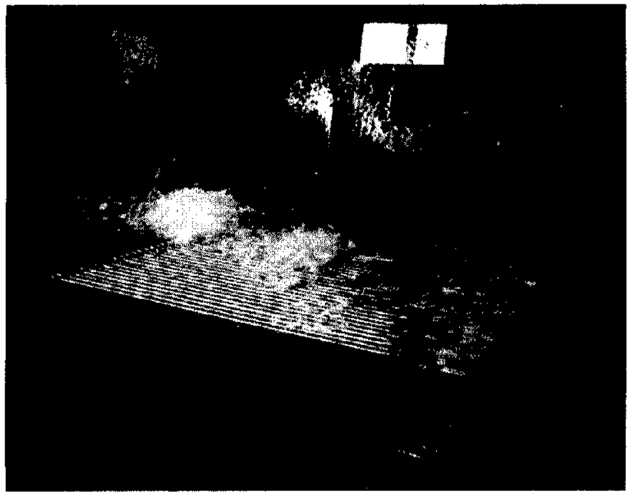


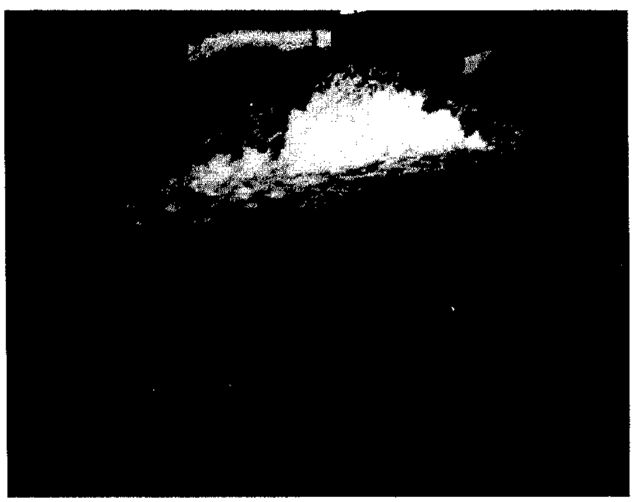
Figure 2-5. - Hydraulic efficiency vs. gutter flow, 1.25 ft by 2.0 ft (0.38 m by 0.61 m) P - 1-1/8 grate.



a. 4 ft (1.22 m) long grate $E = 94.2\%$

$T' = 4.5$ ft (1.37 m) $Q_T = 5.21$ ft^3/s (0.148 m^3/s)

Photo 166-6A



b. 2 ft (0.61 m) long grate $E = 74.7\%$

$T' = 4.5$ ft (1.37 m) $Q_T = 5.26$ ft^3/s (0.149 m^3/s)

Photo 175-13A

Figure 2-6. - Development of splash on the 3.0 ft (0.91 m) wide P - 1-1/8 grate, $Z = 16$, $S_0 = 13\%$.

Table 2-2. - *Maximum efficiency longitudinal slopes for P - 1-1/8 grates*

	L = 2.0 ft (0.61 m)	L = 2.67 ft (0.81 m)	L = 4.0 ft (1.22 m)
1/Z = 1/16	4%	6%	9%
1/Z = 1/24	6%	9%	13%
1/Z = 1/48	>13%	>13%	>13%

At these longitudinal slopes and steeper, the gutter flow strikes the vertical face of the downstream cast steel spacers. Flow which hits the spacer is deflected up and out of the grate inlet in a "rooster tail" splash pattern. Flow energy is small enough at the 1/48 cross slope that splashing does not occur for any gutter flow condition tested.

Figures 2-7 through 2-10 show the relationship between measured width of spread, T', and hydraulic efficiency, E, for the grate sizes tested. As stated in volume 1, the flatter longitudinal slopes are more efficient for the same measured width of spread, T', however, the total gutter flow, Q_T, and in turn, the intercepted flow, Q_I, is considerably less for the flatter slopes with the same measured width of spread as the steeper slopes.

Figures 2-11 through 2-22 present the 12 grate inlet capacity curves for the four P - 1-1/8 grate sizes and three cross slope conditions tested. Hydraulic efficiency of the P - 1-1/8 grate is excellent for all gutter flow conditions when the grate is long enough to accept the flow without striking the downstream spacer blocks. When the flow strikes the downstream spacer blocks, the hydraulic efficiency of the grate decreases quite rapidly for steeper longitudinal slopes. This is indicated in figures 2-12, 2-14, 2-16, 2-17, and 2-18 by the sharp reversal in the hydraulic efficiency curves.

As noted in figure 2-1, the cast spacers are 24/16 - 13/16 = 11/16 in (17.5 mm) from the end of the grate inlet. Relocating the cast spacers flush with the ends of the longitudinal bars would increase the effective length of the P - 1-1/8 grates by 1-3/8 in (35 mm).

<u>Summary</u>

As stated previously, the P - 1-1/8 grate is bicycle safe and hydraulically efficient. Its major drawback, as described in chapter 12 of volume 1, is its poor debris handling capability.

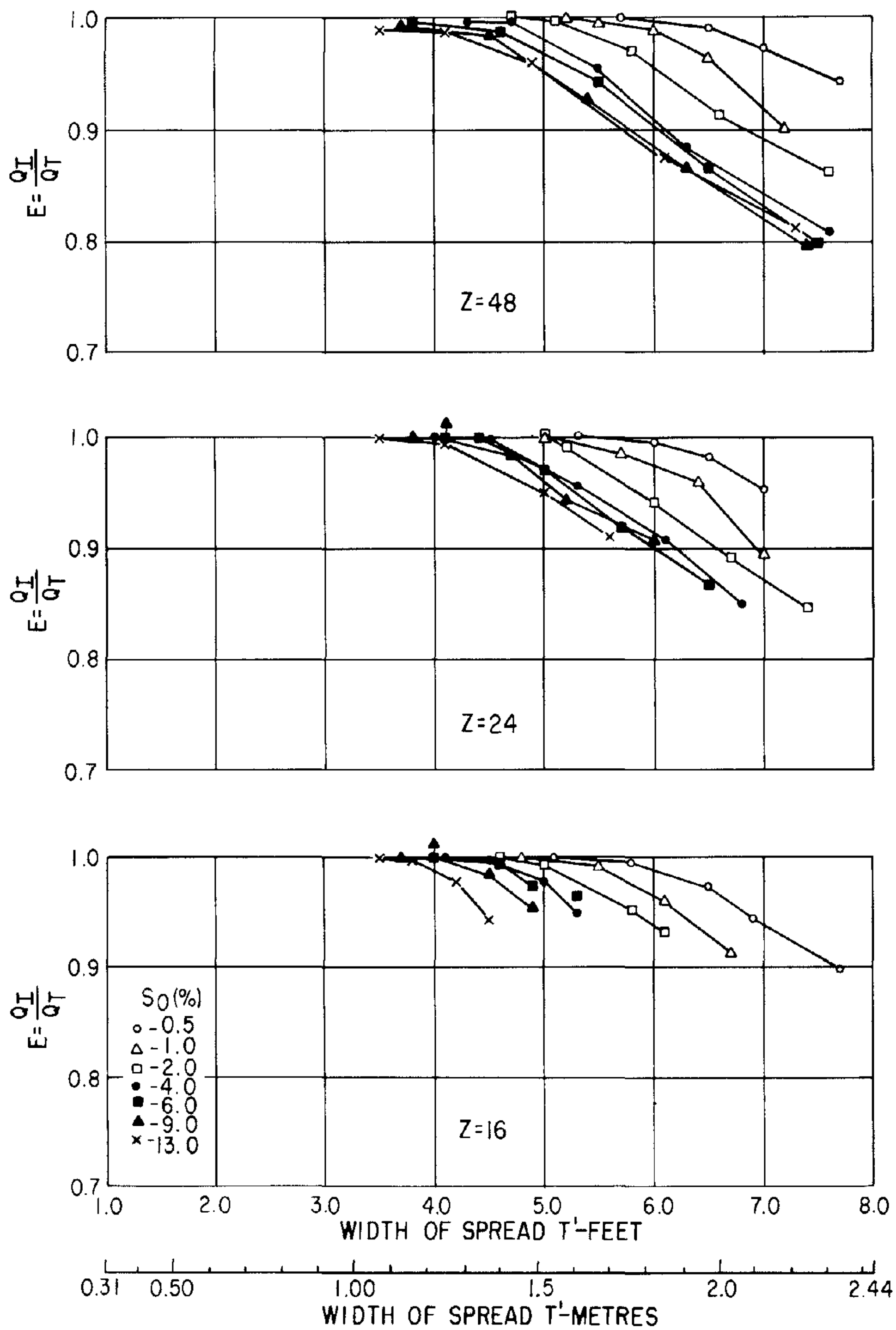


Figure 2-7. - Hydraulic efficiency vs. width of spread 3.0 ft by 4.0 ft (0.91 m by 1.22 m) P - 1-1/8 grate.

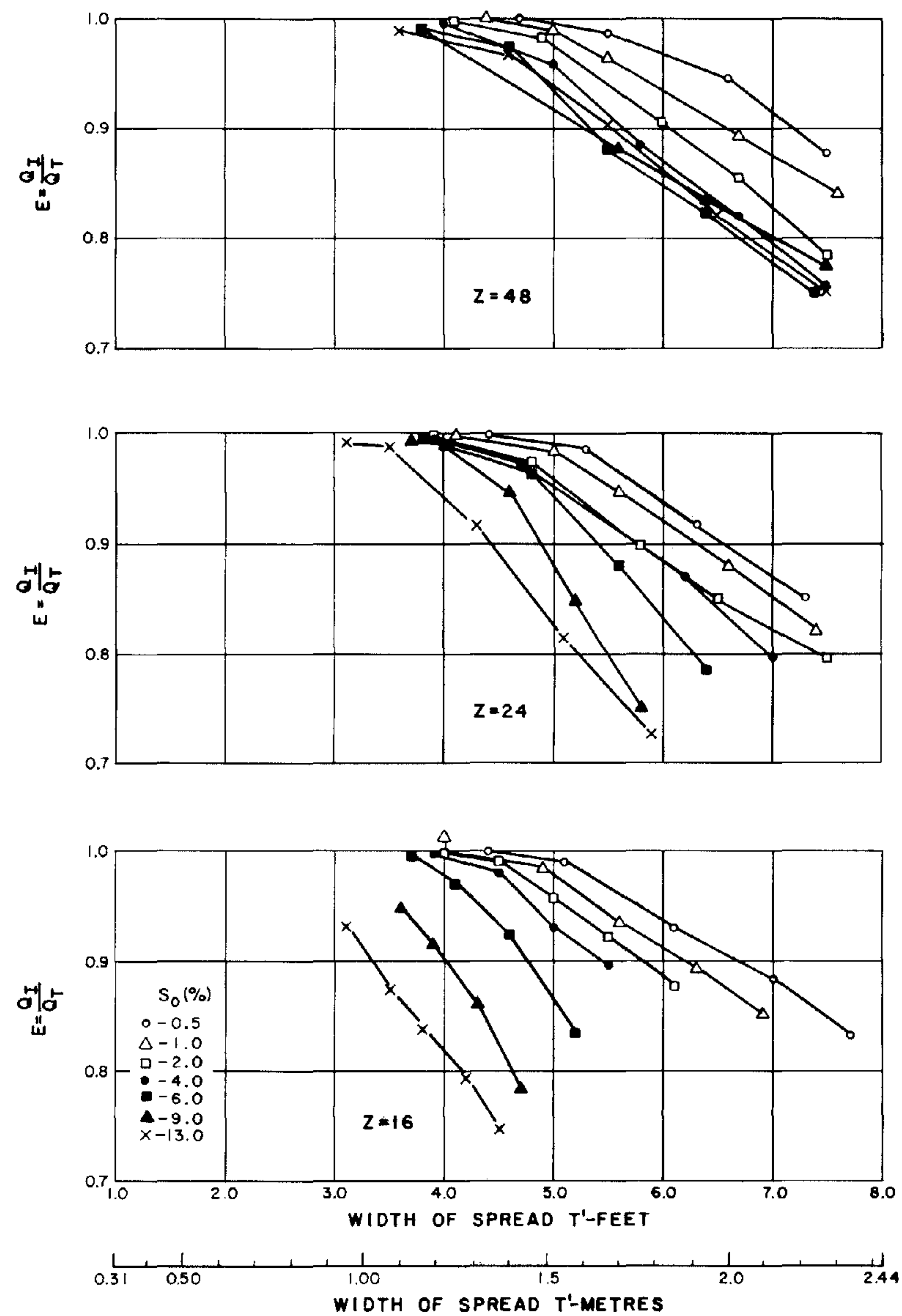


Figure 2-8. - Hydraulic efficiency vs. width of spread
3.0 ft by 2.0 ft (0.91 m by 0.61 m)
P - 1-1/8 grate.

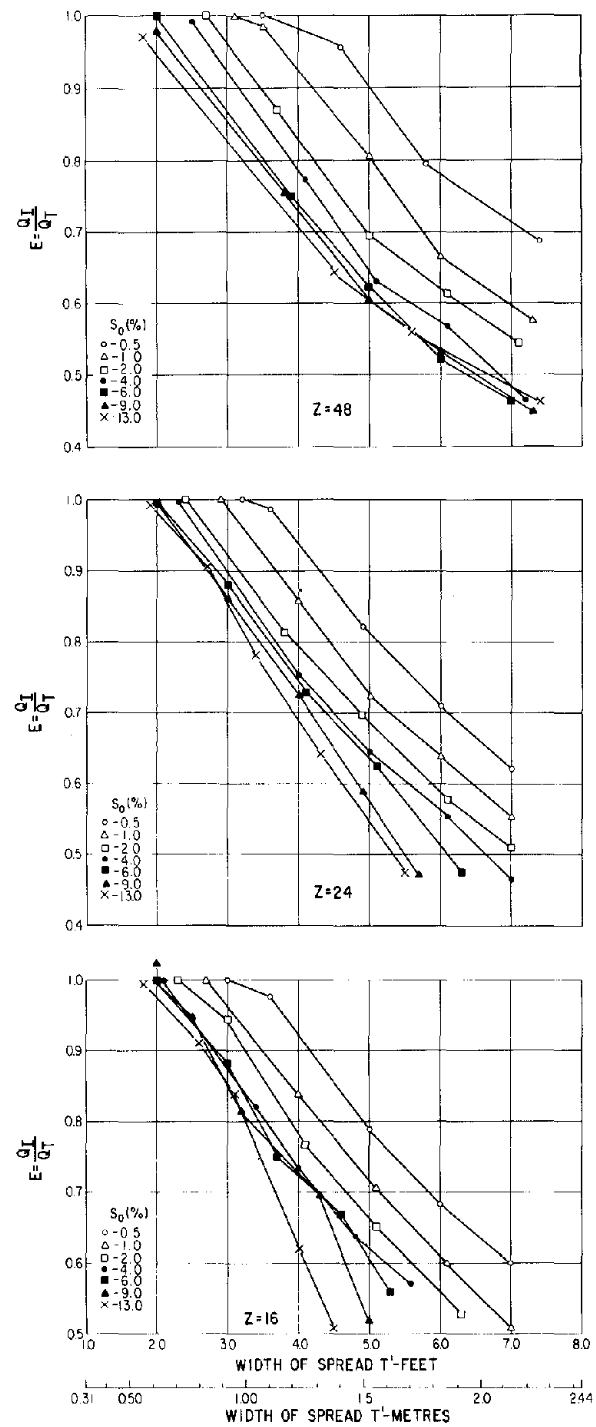


Figure 2-9. - Hydraulic efficiency vs. width of spread 1.25 ft by 2.67 ft (0.38 m by 0.81 m) P - 1-1/8 grate.

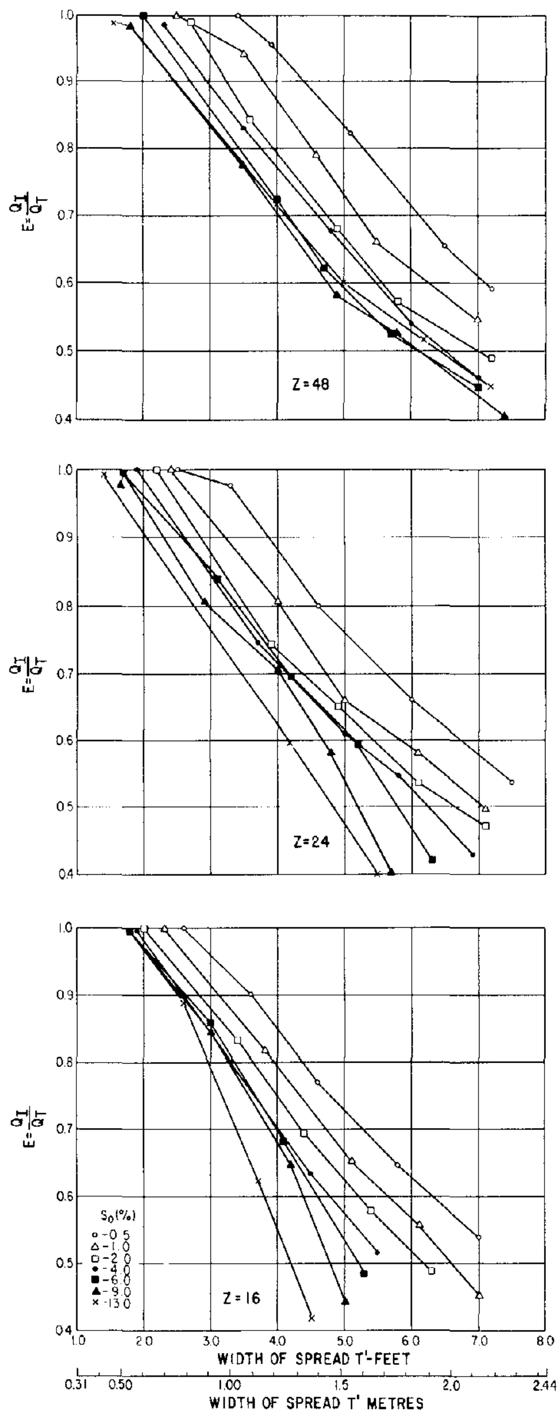


Figure 2-10. - Hydraulic efficiency vs. width of spread 1.25 ft by 2.0 ft (0.38 m by 0.61 m) P - 1-1/8 grate.

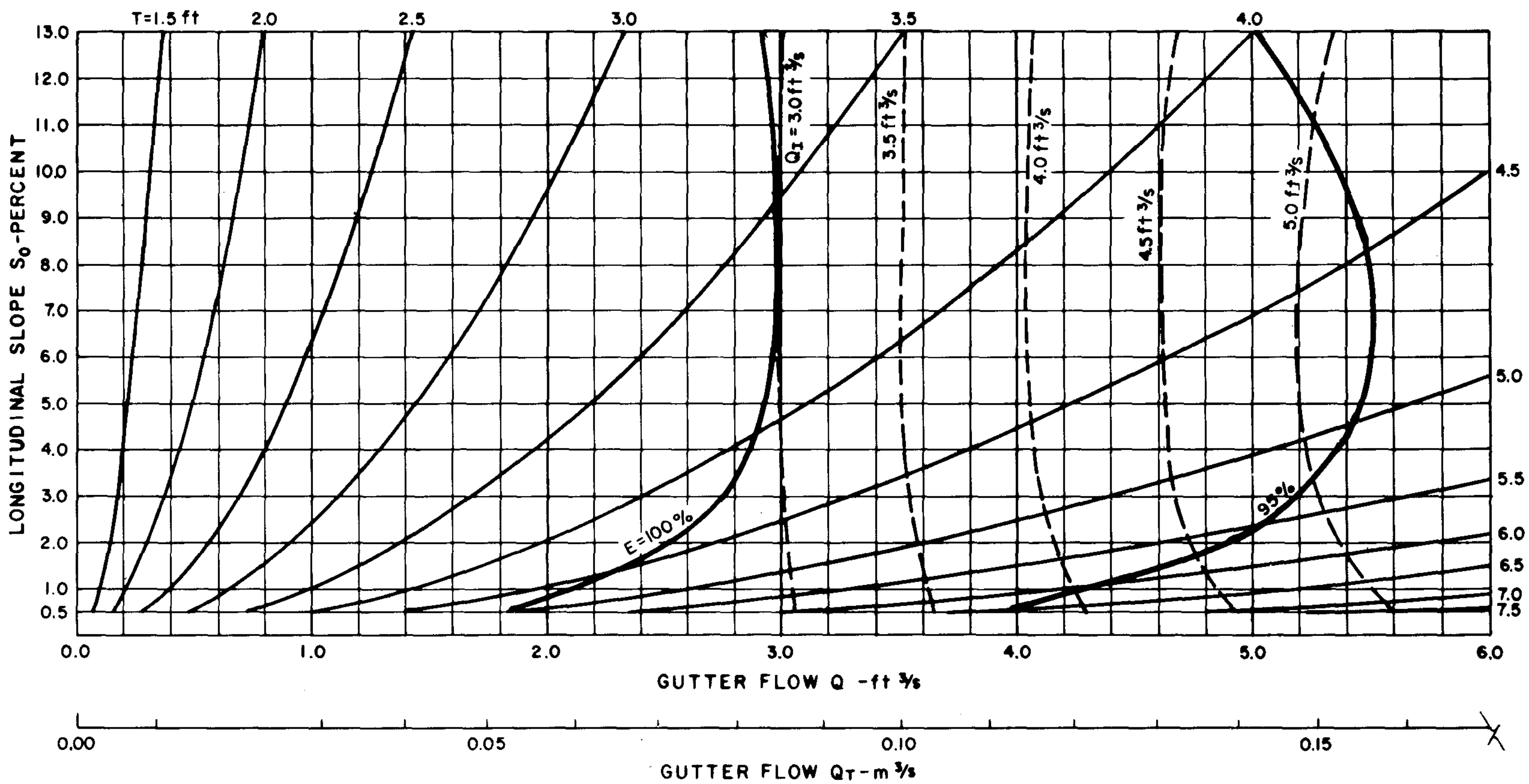


Figure 2-11. - Grate inlet capacity curves, 3.0 ft by 4.0 ft (0.91 m by 1.22 m)
P - 1-1/8 grate, Z = 16.

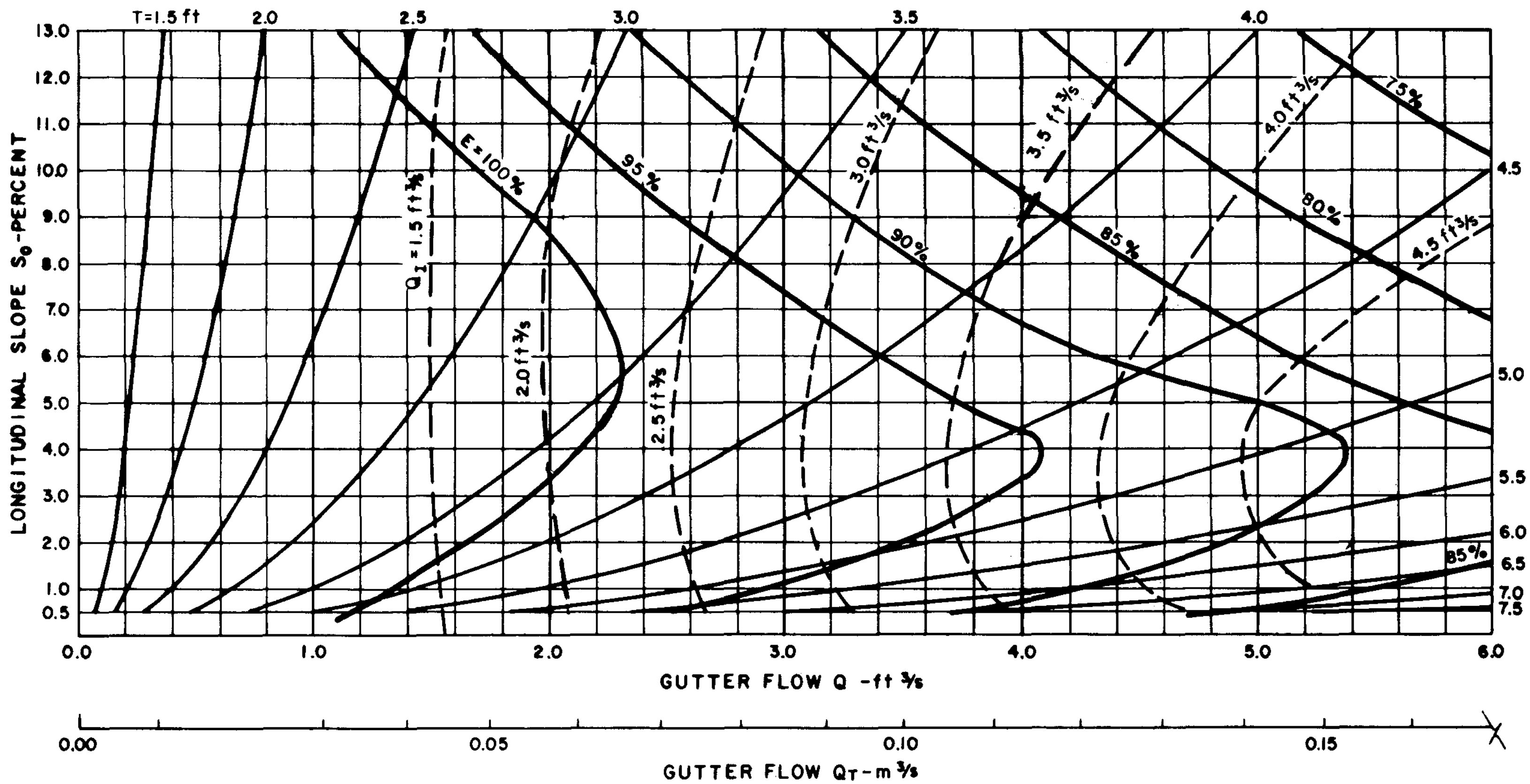


Figure 2-12. - Grate inlet capacity curves, 3.0 ft by 2.0 ft (0.91 m by 0.61 m)
P - 1-1/8 grate, Z = 16.

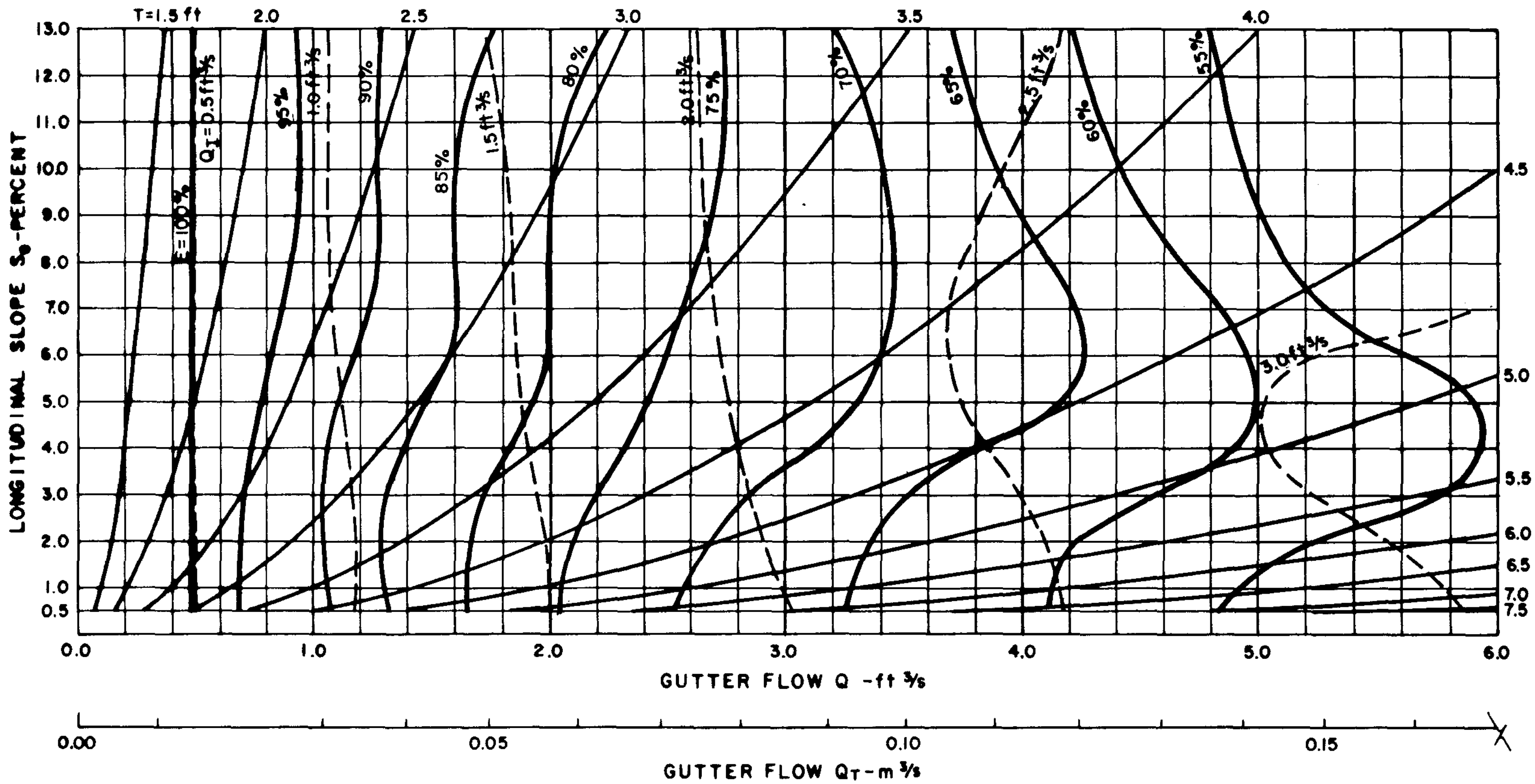


Figure 2-13. - Grate inlet capacity curves, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) P - 1-1/8 grate, Z = 16.

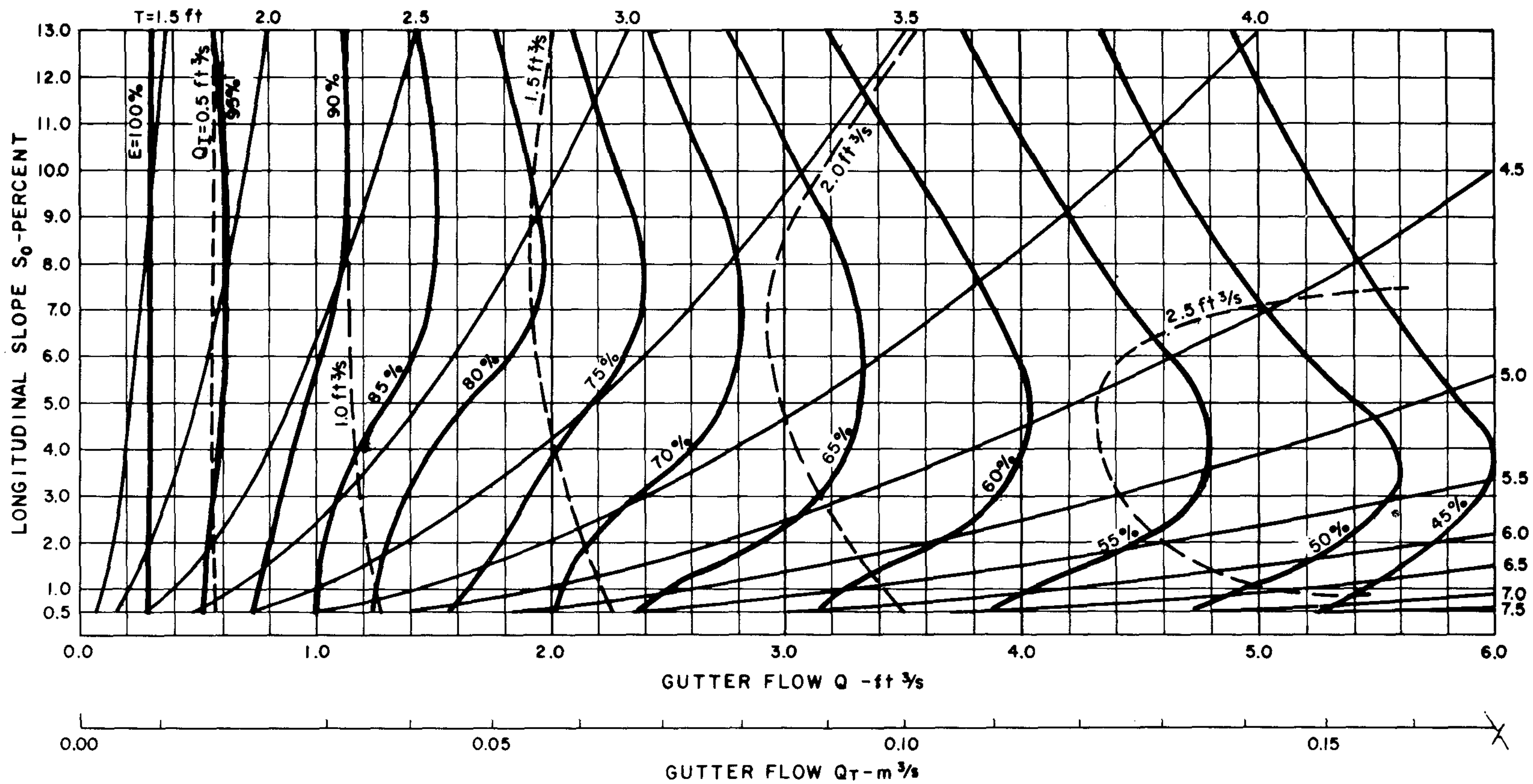


Figure 2-14. - Grate inlet capacity curves, 1.25 ft by 2.0 ft (0.38 m by 0.61 m)
P - 1-1/8 grate, Z = 16.

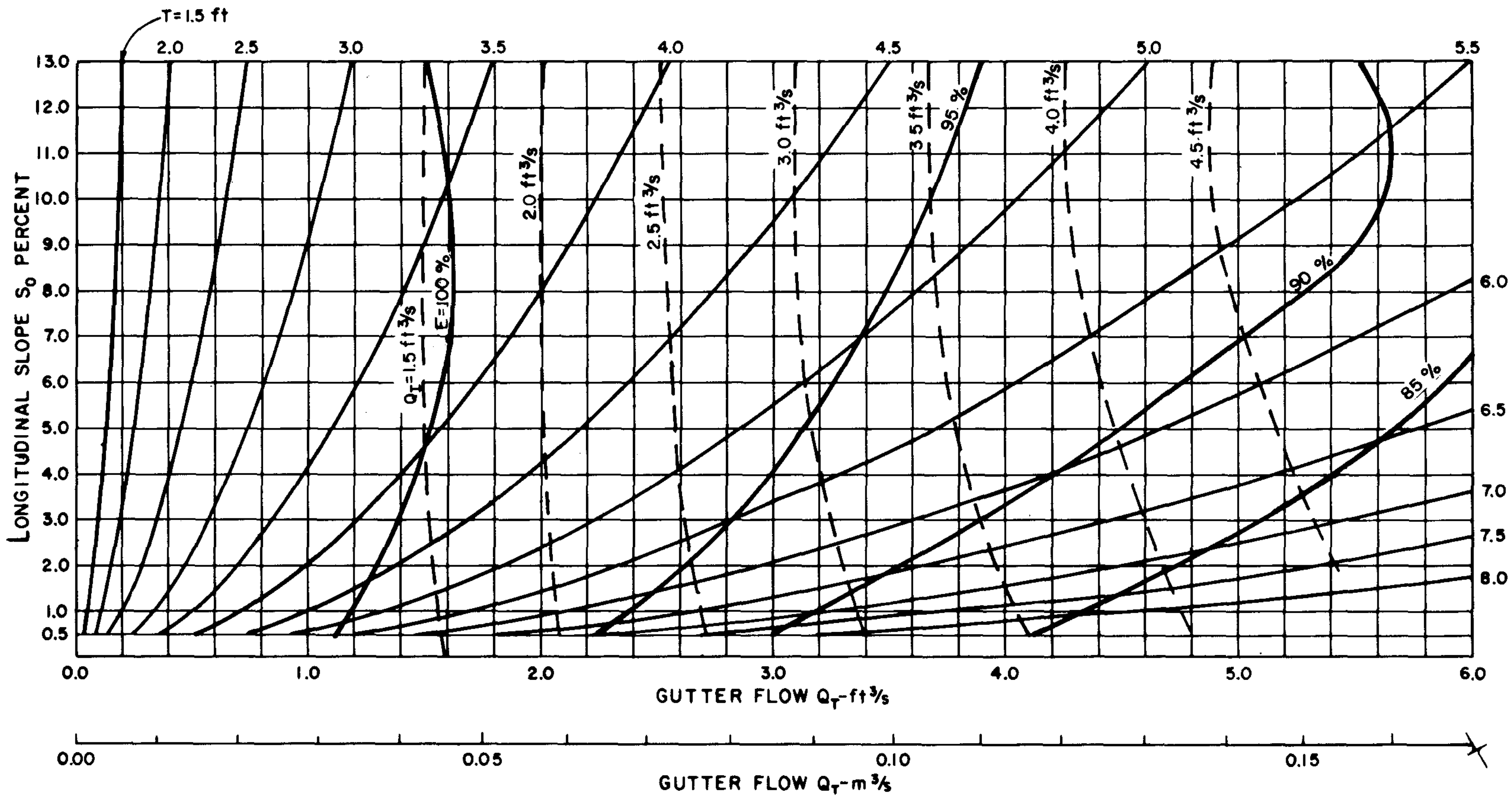


Figure 2-15. - Grate inlet capacity curves, 3.0 ft by 4.0 ft (0.91 m by 1.22 m) P - 1-1/8 grate, Z = 24.

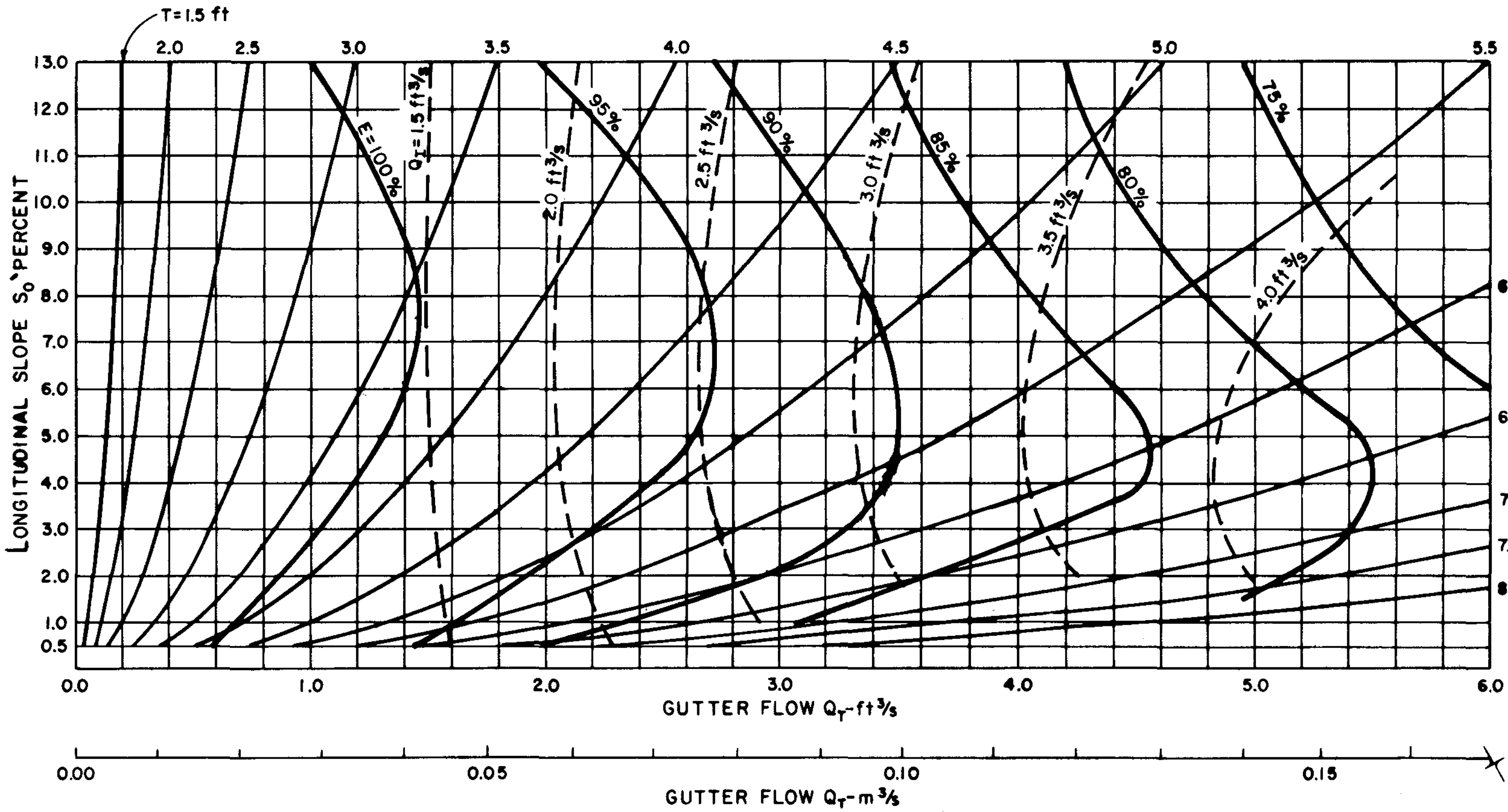


Figure 2-16. - Grate inlet capacity curves, 3.0 ft by 2.0 ft (0.91 m by 0.61 m) P - 1-1/8 grate, Z = 24.

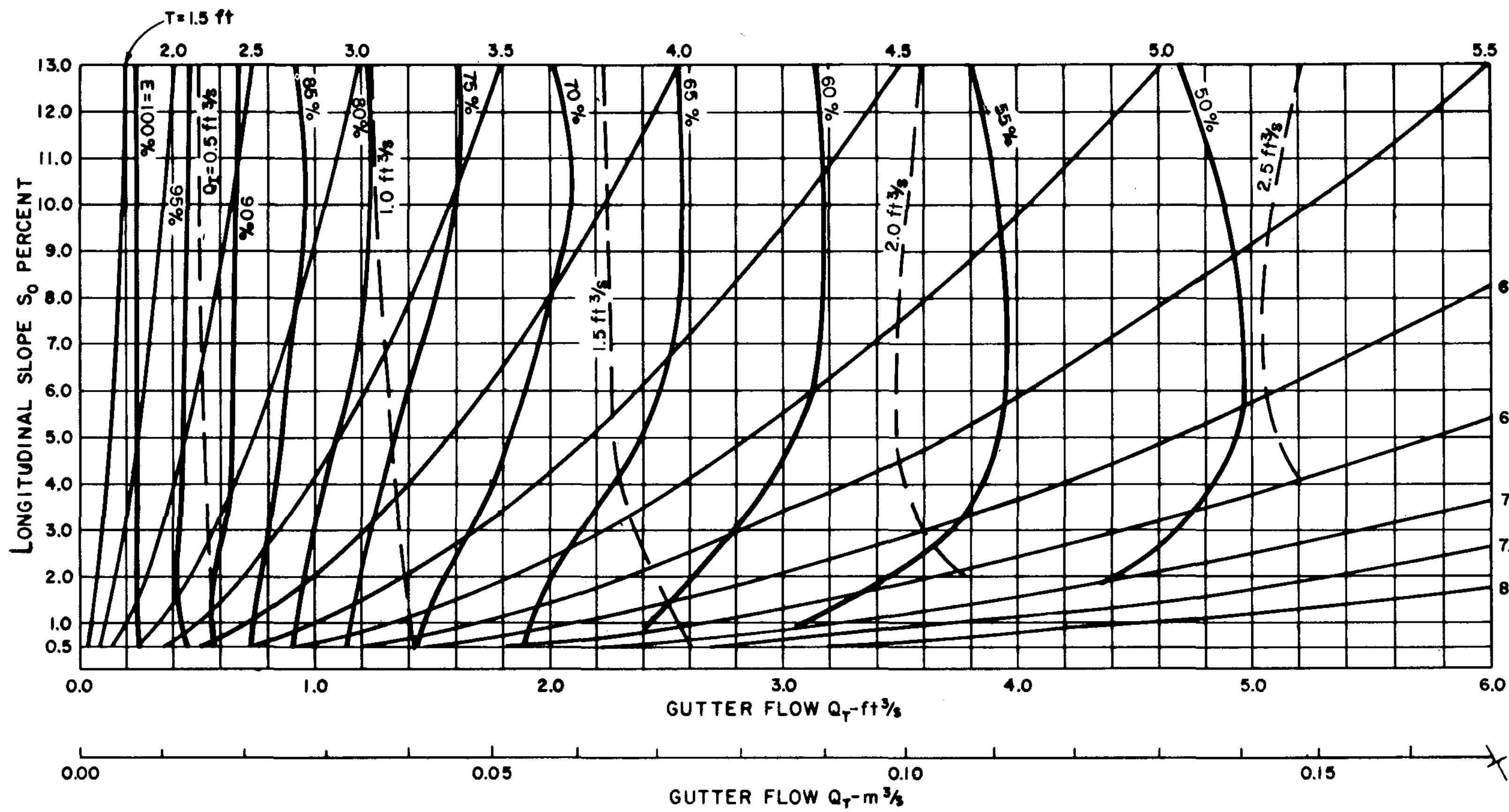


Figure 2-17. - Grate inlet capacity curves, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) P - 1-1/8 grate, Z = 24.

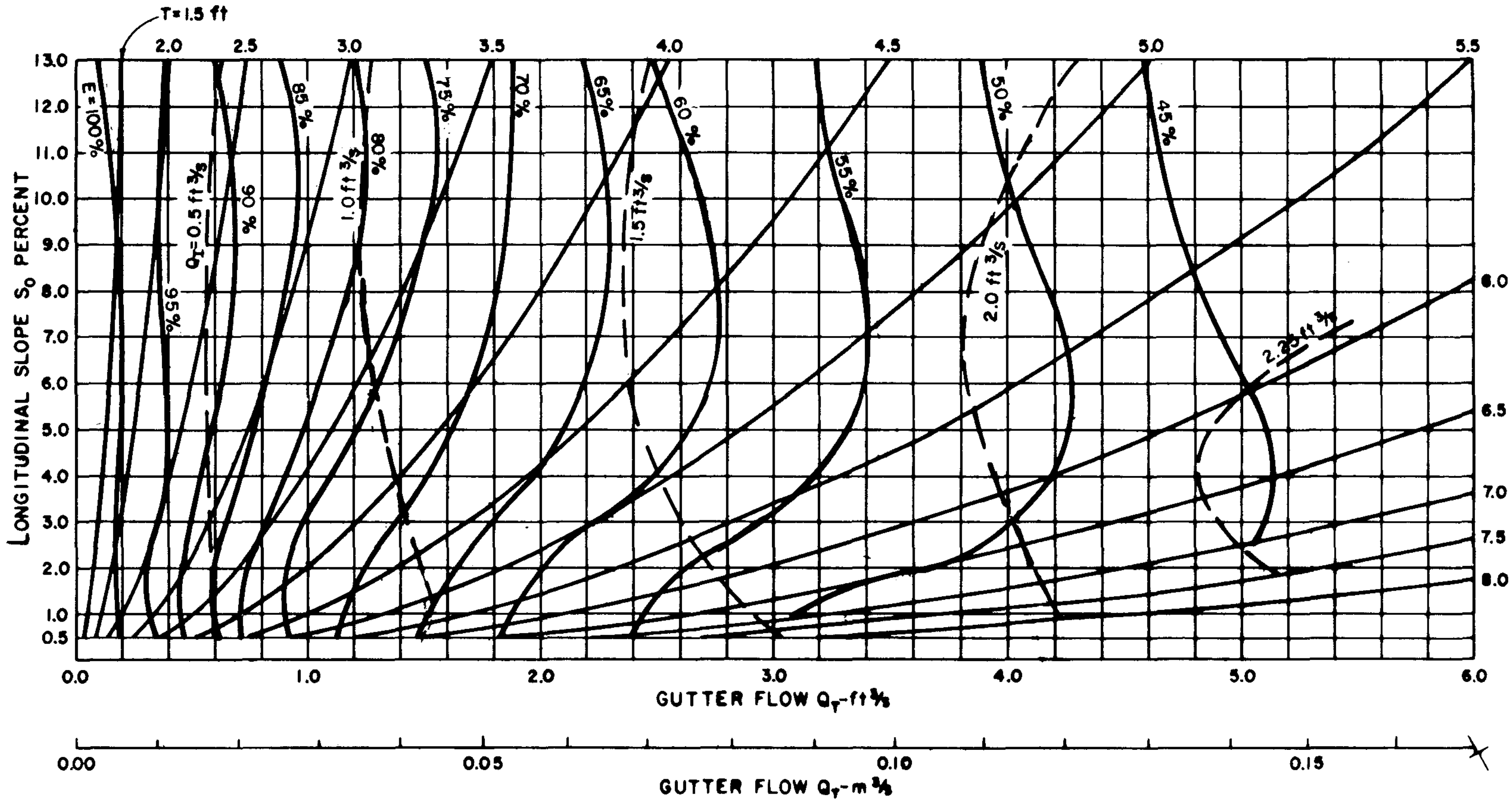


Figure 2-18. - Grate inlet capacity curves, 1.25 ft by 2.0 ft (0.38 m by 0.61 m) P - 1-1/8 grate, Z = 24.

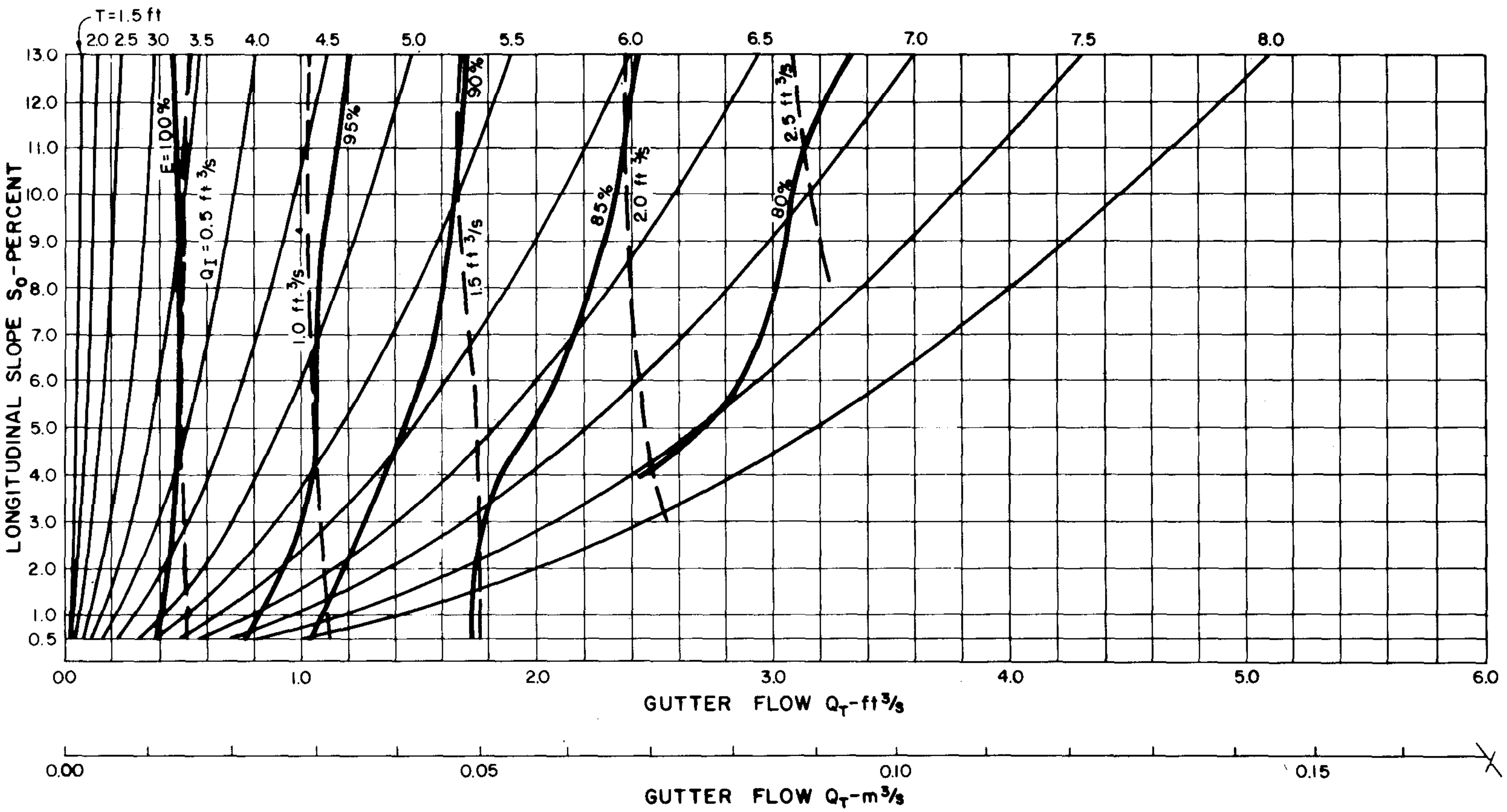


Figure 2-19. - Grate inlet capacity curves, 3.0 ft by 4.0 ft (0.91 m by 1.22 m) P - 1-1/8 grate, Z = 48.

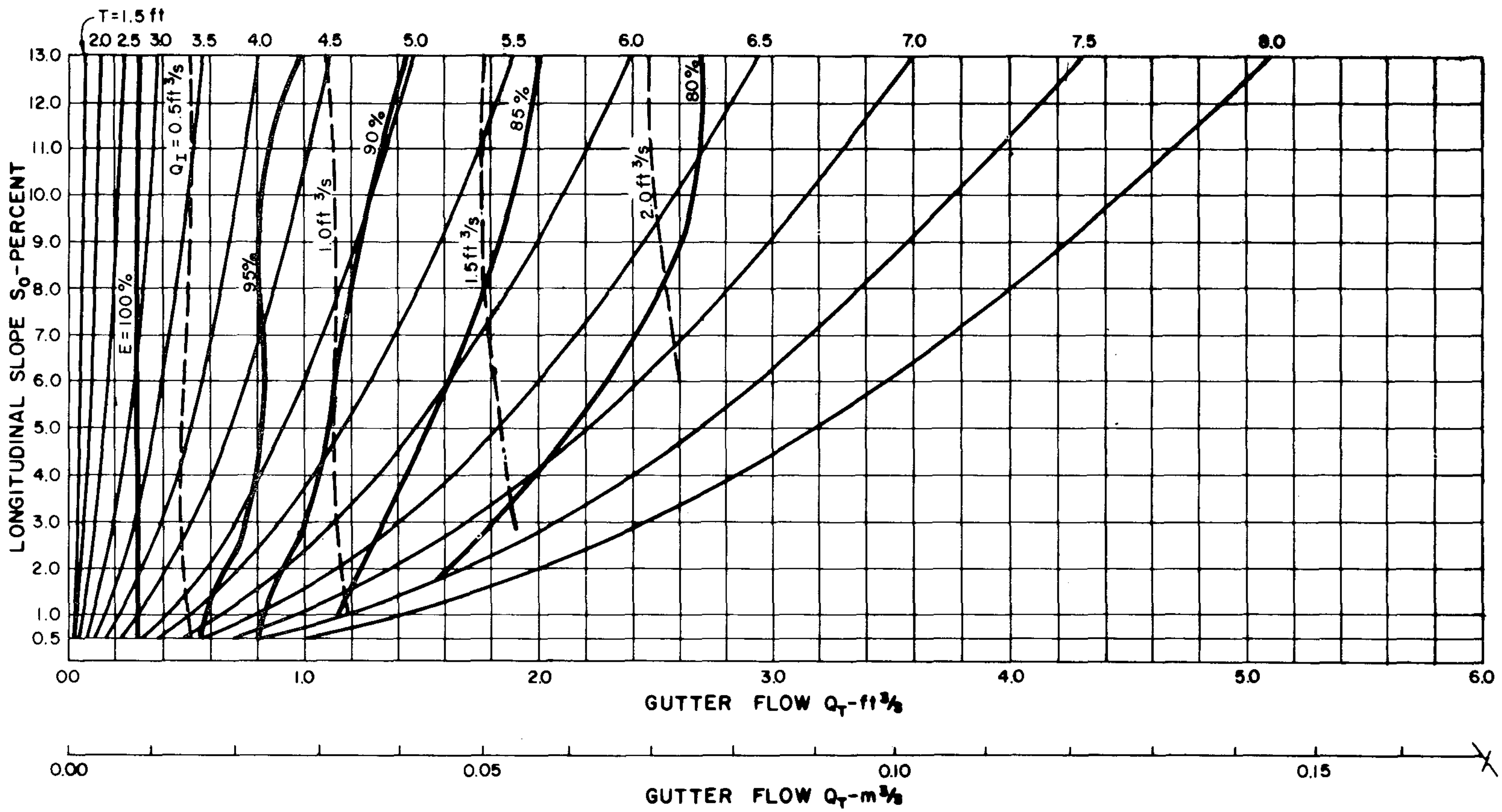


Figure 2-20. - Grate inlet capacity curves, 3.0 ft by 2.0 ft (0.91 m by 0.61 m) P - 1-1/8 grate, Z = 48.

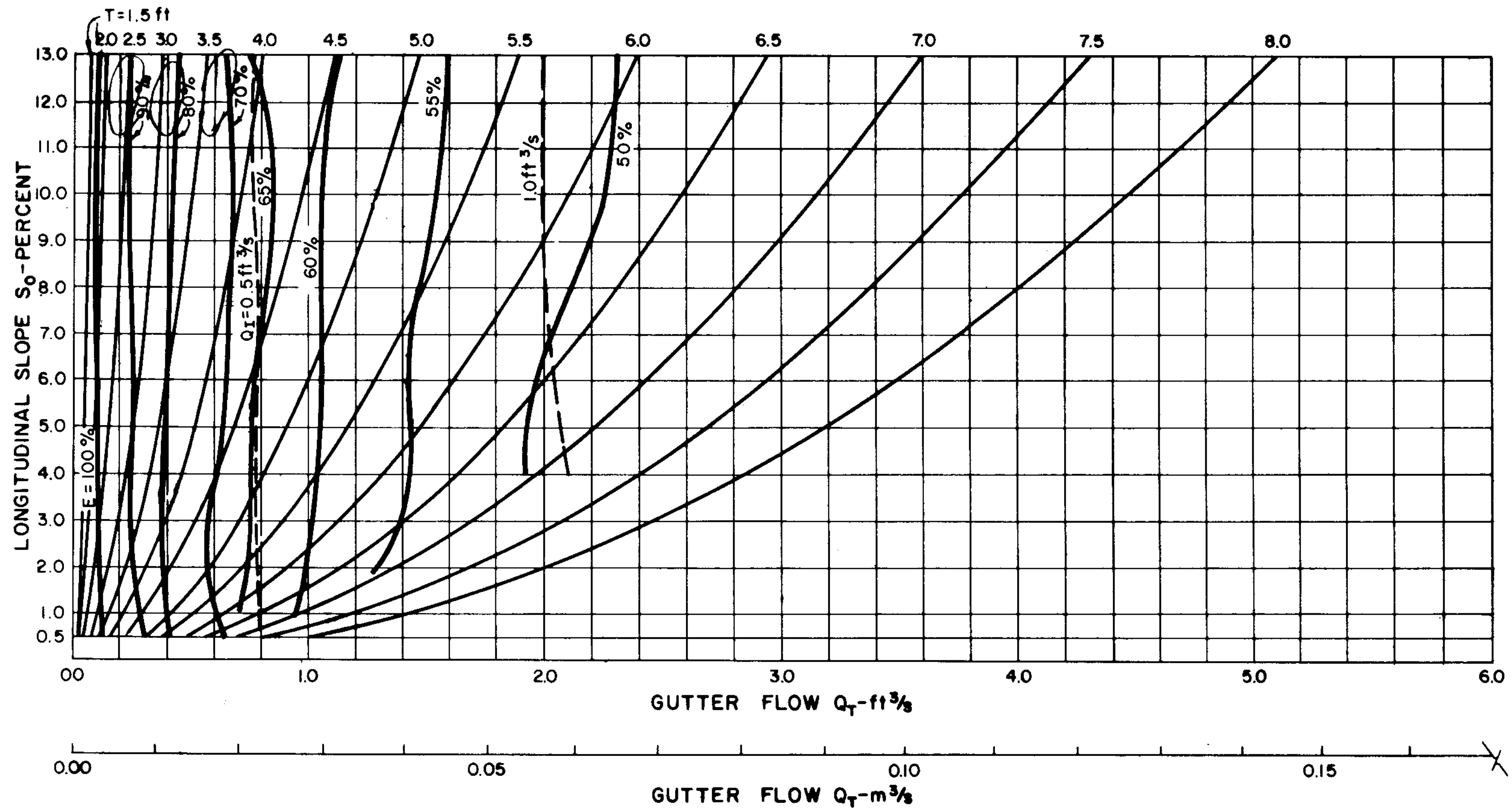


Figure 2-21. - Grate inlet capacity curves, 1.25 ft by 2.67 ft (0.38 m by 0.81 m)
P - 1-1/8 grate, Z = 48.

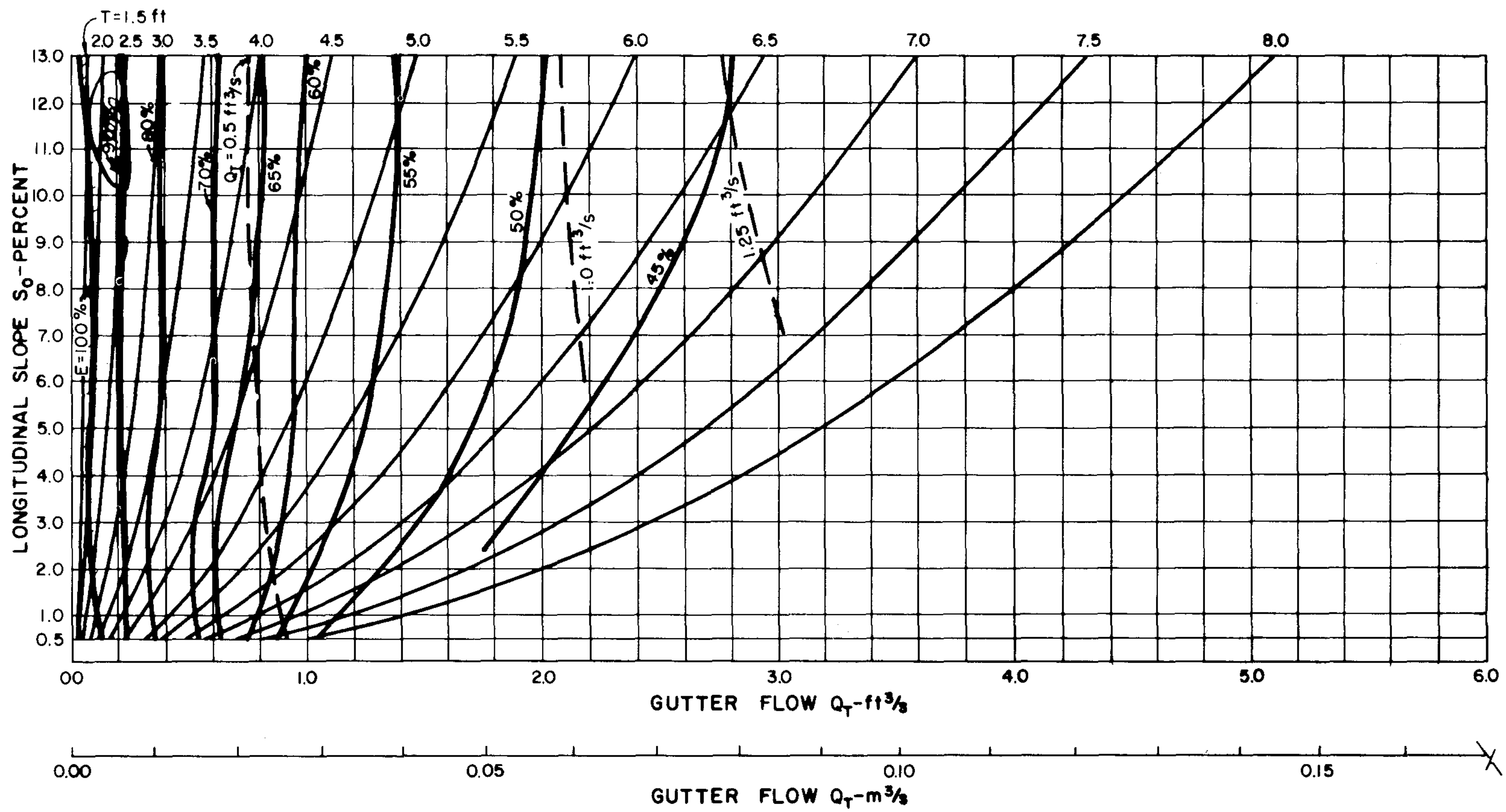


Figure 2-22. - Grate inlet capacity curves, 1.25 ft by 2.0 ft (0.38 m by 0.61 m)
P - 1-1/8 grate, Z = 48.

Figures 2-23 through 2-25 show the performance of six grate sizes (including the two sizes in chapter 12 of volume 1) for a given width of spread, T', as the longitudinal slope, S_0, varies. The width of spread, T', chosen for each cross slope is near the maximum tested on the hydraulic test facility. Several conclusions can be made concerning the P - 1-1/8 grate from studying these three figures:

1. Grate width is an important variable in determining the hydraulic efficiency of the P - 1-1/8 grate. A greater percentage increase in hydraulic efficiency, E, is realized with an incremental increase in grate width as compared to the same increase in grate length. This is particularily noticable for the 1/48 cross slopes, figure 2-25. (Note the increase in hydraulic efficiency, E, for the 2.0 ft (0.61 m) long grate as the width increases from 1.25 ft (0.38 m) to 3.0 ft (0.91 m). Keeping the width the same, 2.0 ft (0.61 m), and doubling the length to 4.0 ft (1.22 m) results in a minimal increase in efficiency.)

2. For high energy gutter flow conditions, the hydraulic efficiency of the P - 1-1/8 grate decreases rapidly for inadequate grate lengths. The performance curves for the 2 ft and 2.67 ft (0.61 m and 0.81 m) long grates in figures 2-23 and 2-24 clearly illustrate the rapid decrease in efficiency for these shorter grate lengths. The limiting longitudinal slopes given in table 2-2, also are verified by these curves.

To achieve the desired hydraulic characteristics of the P - 1-1/8 grate, hydraulic design engineers should be cognizant of the length limitations of this grate and choose a grate length consistent with the design gutter flow conditions.

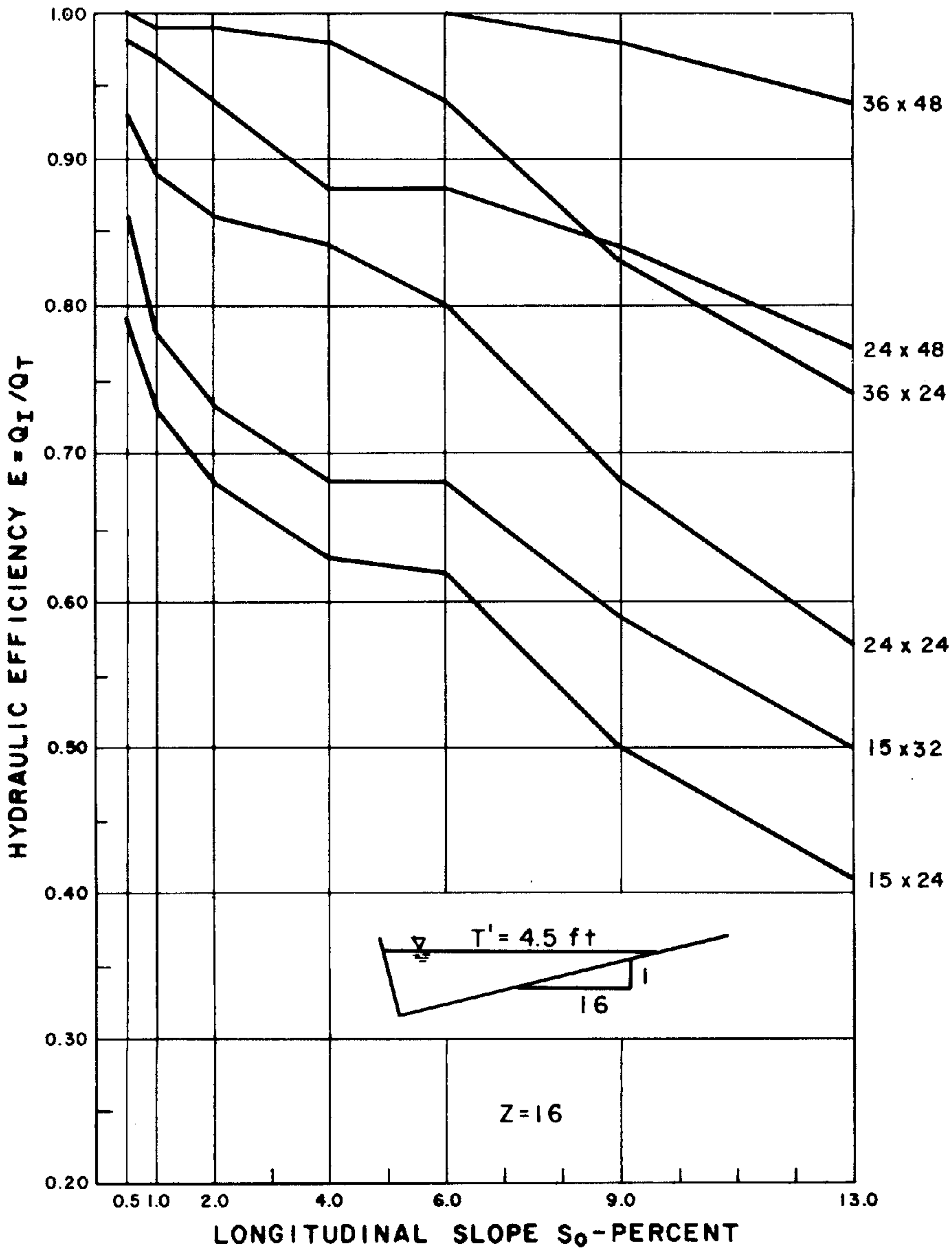


Figure 2-23. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, P - 1-1/8 grate, T' = 4.5 ft (1.37 m), Z = 16.

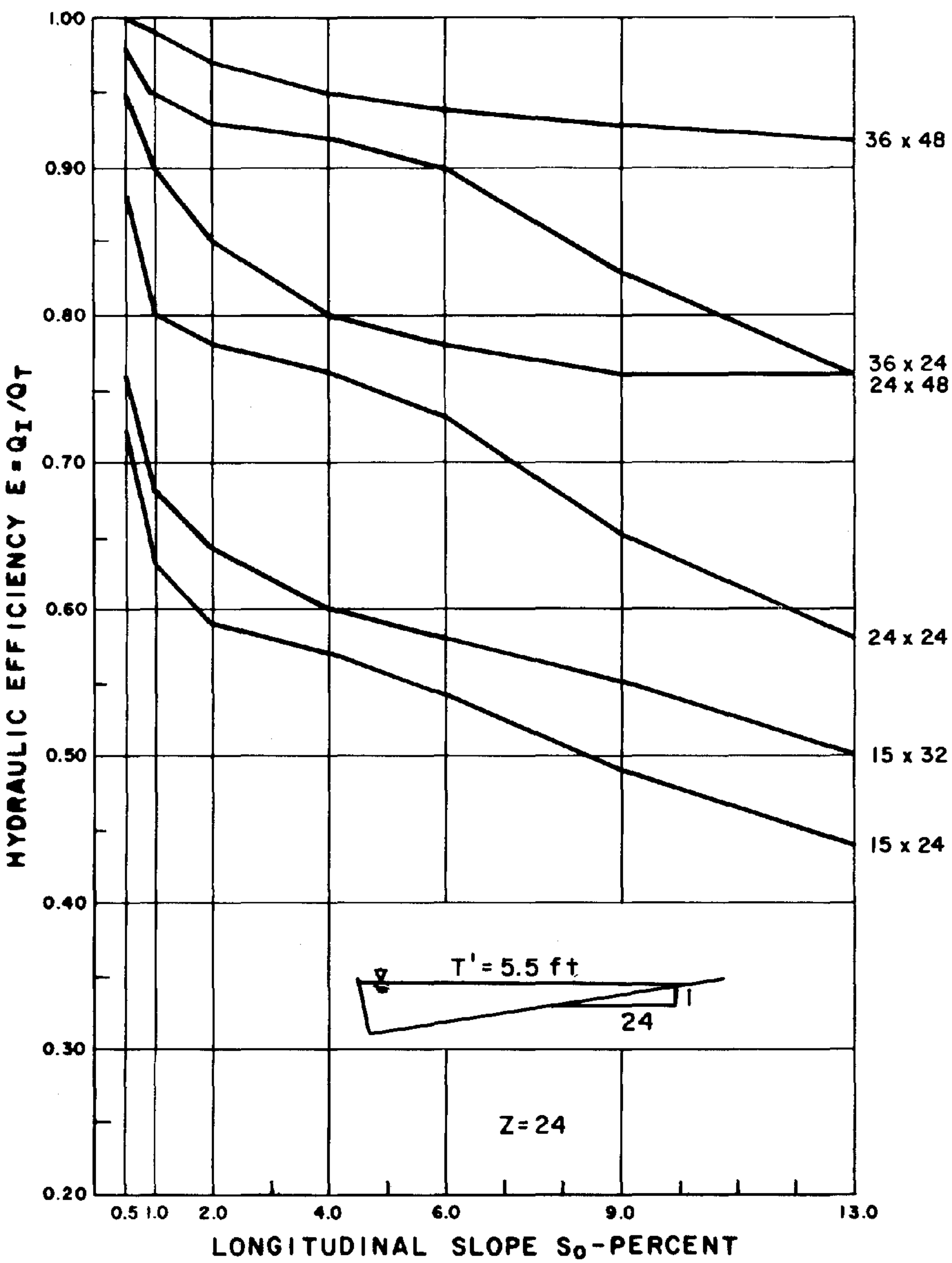


Figure 2-24. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, P - 1-1/8 grate, T' = 5.5 ft (1.68 m), Z = 24.

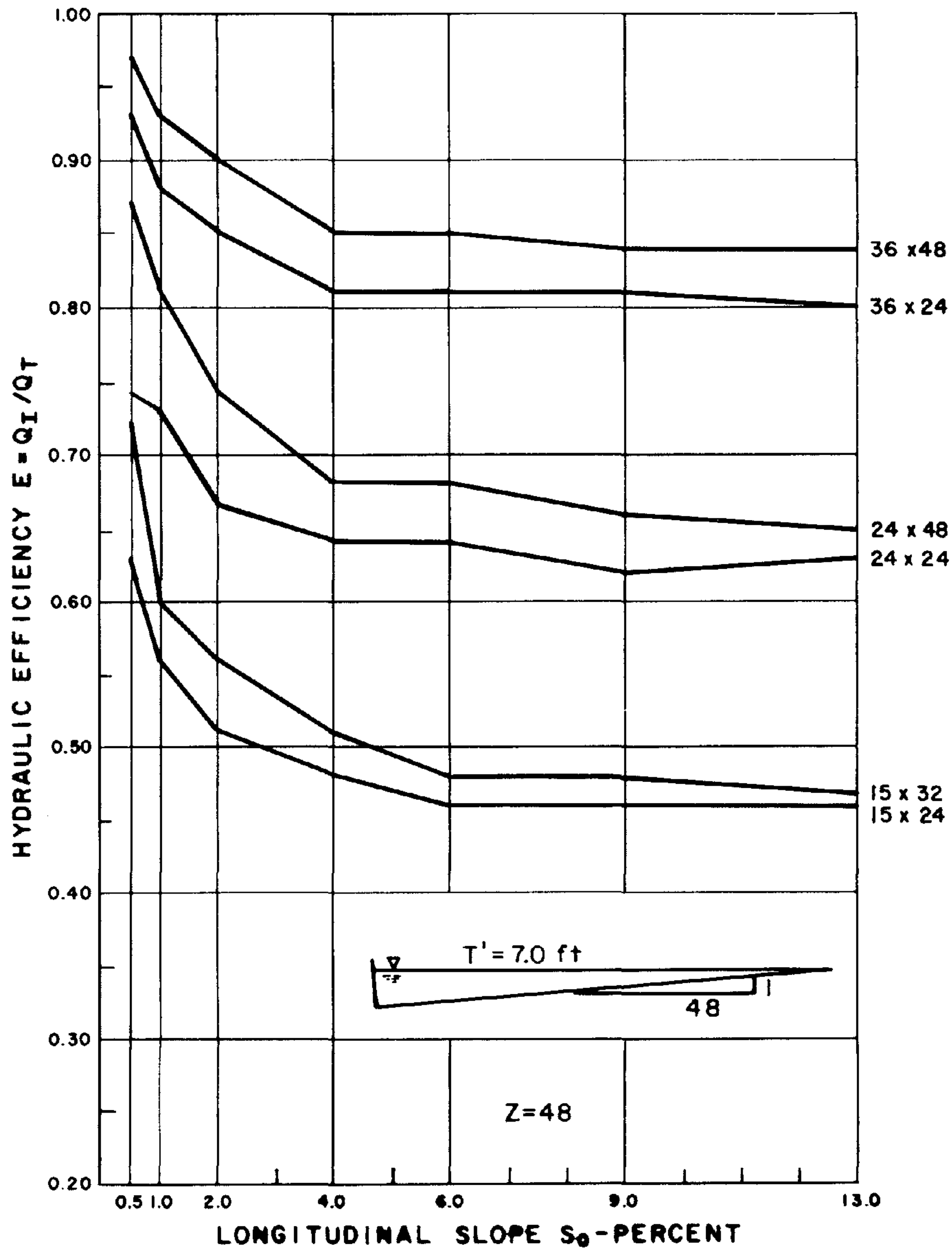


Figure 2-25. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, P - 1-1/8 grate, T' = 7.0 ft (2.13 m), Z = 48.

CHAPTER 3

THE PARALLEL BAR GRATE WITH TRANSVERSE RODS -

P - 1-7/8 - 4

This chapter contains the results of the additional hydraulic test conducted on four sizes of the parallel bar grate with transverse rods P - 1-7/8 - 4 (chapter 11, volume 1). The grate consists of 1/4 in (6.35 mm) wide longitudinal bars on 1-7/8 in (47.6 mm) centers and 3/8 in (9.53 mm) transverse rods electroforged flush to the top of the longitudinal bars on 4 in (102 mm) centers. The four grate sizes tested are illustrated in figure 3-1. Table 3-1 summarizes the required depth of bearing bars for the four grate inlet sizes. Details of the structural analysis are covered in chapter 2 of volume 1. A simple beam analysis was used for the three smaller inlet sizes and a computer program called the STR5 (described in volume 1) was used to analyze the 3.0 ft by 4.0 ft (0.91 m by 1.22 m) size inlet. Since the longitudinal bars are 1-7/8 in (47.6 mm) centers and the transverse bars are 4 in (102 mm) centers, the grate will be referred to as P - 1-7/8 - 4 grate.

Hydraulics

The hydraulic test results for the P - 1-7/8 - 4 grates are shown in figures 3-2 through 3-5. For a specific gutter flow, Q_T, and longitudinal slope, S_0, the steeper cross slopes, 1/Z, result in higher hydraulic efficiencies. For both the 1.25 ft and 3 ft (0.38 m and 0.91 m) wide grates, the longer lengths of grate are more efficient for the same gutter flow conditions due to the added side flow.

For low energy flows ($S_0 < 5\%$ for $1/Z = 1/16$, $S_0 < 7\%$ for $1/Z = 1/24$, and $S_0 < 13\%$ for $1/Z = 1/48$) the width of the P - 1-7/8 - 4 grate has more impact on its hydraulic efficiency than its length. As shown with the P - 1-1/8 grate, the 3 ft by 2 ft (0.91 m by 0.61 m) size of the P - 1-7/8 - 4 grate is also more efficient than the 2 ft by 4 ft (0.61 m by 1.22 m) size, figures 3-3 of this volume and 11-2 of volume 1.

The 3/8 in (9.53 mm) rods at the surface of the P - 1-7/8 - 4 grate caused considerable splash at higher energy gutter flow conditions. It is evident in figures 3-2 through 3-5, that for a constant gutter flow, Q_T, hydraulic efficiency, E, increases with an increase in longitudinal slope, S_0, to a point, and then decreases at a rapid rate. This same phenomena occurred with the test results for the 2 ft by 4 ft (0.61 m by 1.22 m) and 2 ft by 2 ft (0.61 m by 0.61 m) P - 1-7/8 - 4 grates reported in volume 1. By studying these figures and the grate inlet capacity curves, the maximum efficiency

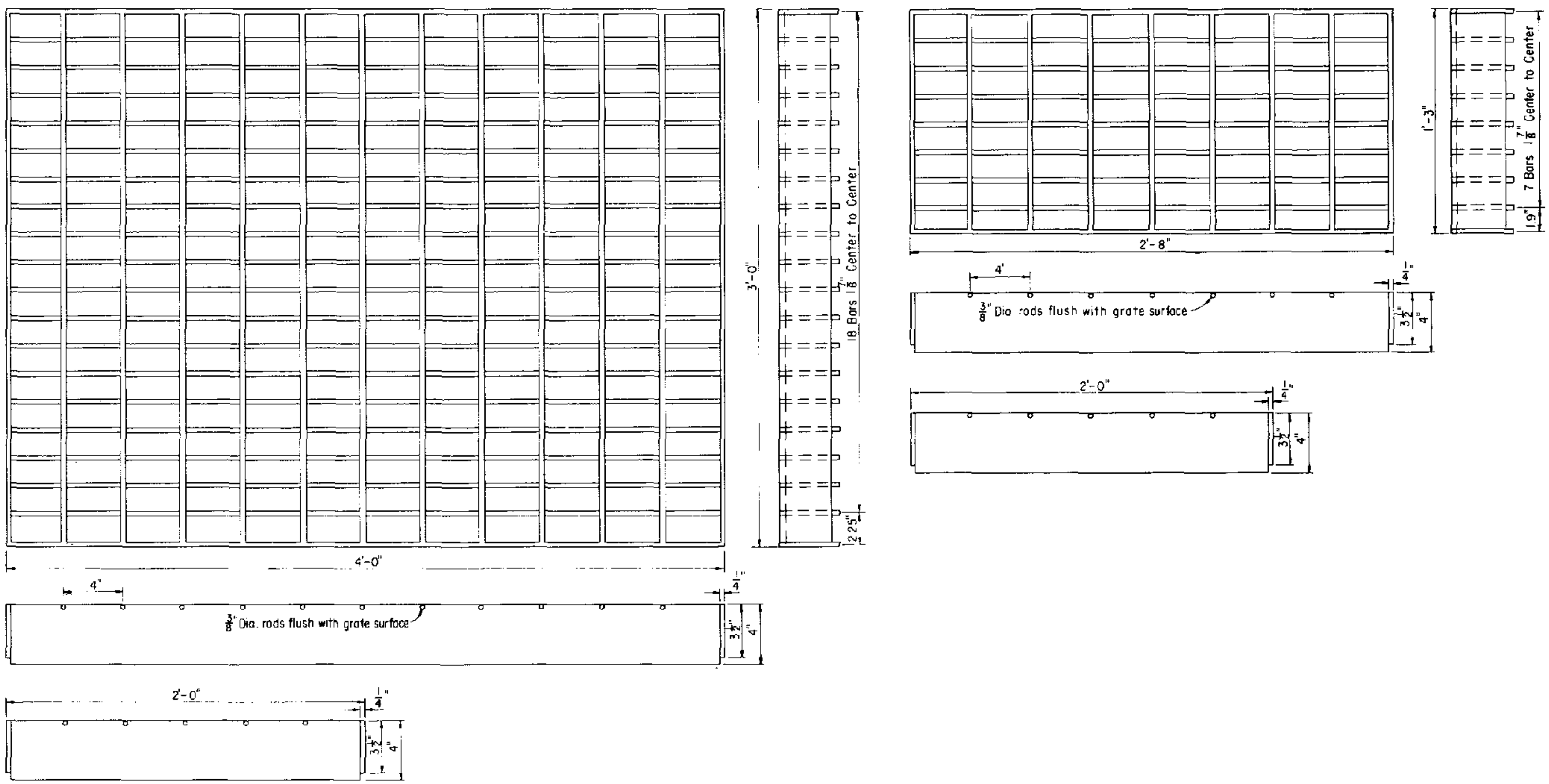


Figure 3-1. - Fabricated steel P - 1-7/8 - 4 grate.

Table 3-1. - *Required depth of bearing bars for P - 1-7/8 - 4 grates*

Bar thickness		3.0 by 4.0 ft (0.91 by 1.22 m) Span (S) = 4.0 ft (1.22 m)		3.0 by 2.0 ft (0.91 by 0.61 m) S = 2.0 ft (0.61 m)		1.25 by 2.67 ft (0.38 by 0.81 m) S = 2.67 ft (0.81 m)		1.25 by 2.0 ft (0.38 by 0.61 m) S = 2.0 ft (0.61 m)	
in	(mm)	in	(mm)	in	(mm)	in	(mm)	in	(mm)
0.50	(12.70)	3.20	(81.3)	2.76	(70.1)	3.28	(83.3)	2.76	(70.1)
0.375	(9.53)	3.90	(99.1)	3.18	(80.8)	3.78	(96.0)	3.18	(80.8)
0.25	(6.35)	4.90	(124)	3.90	(99.1)	4.63	(118)	3.90	(99.1)

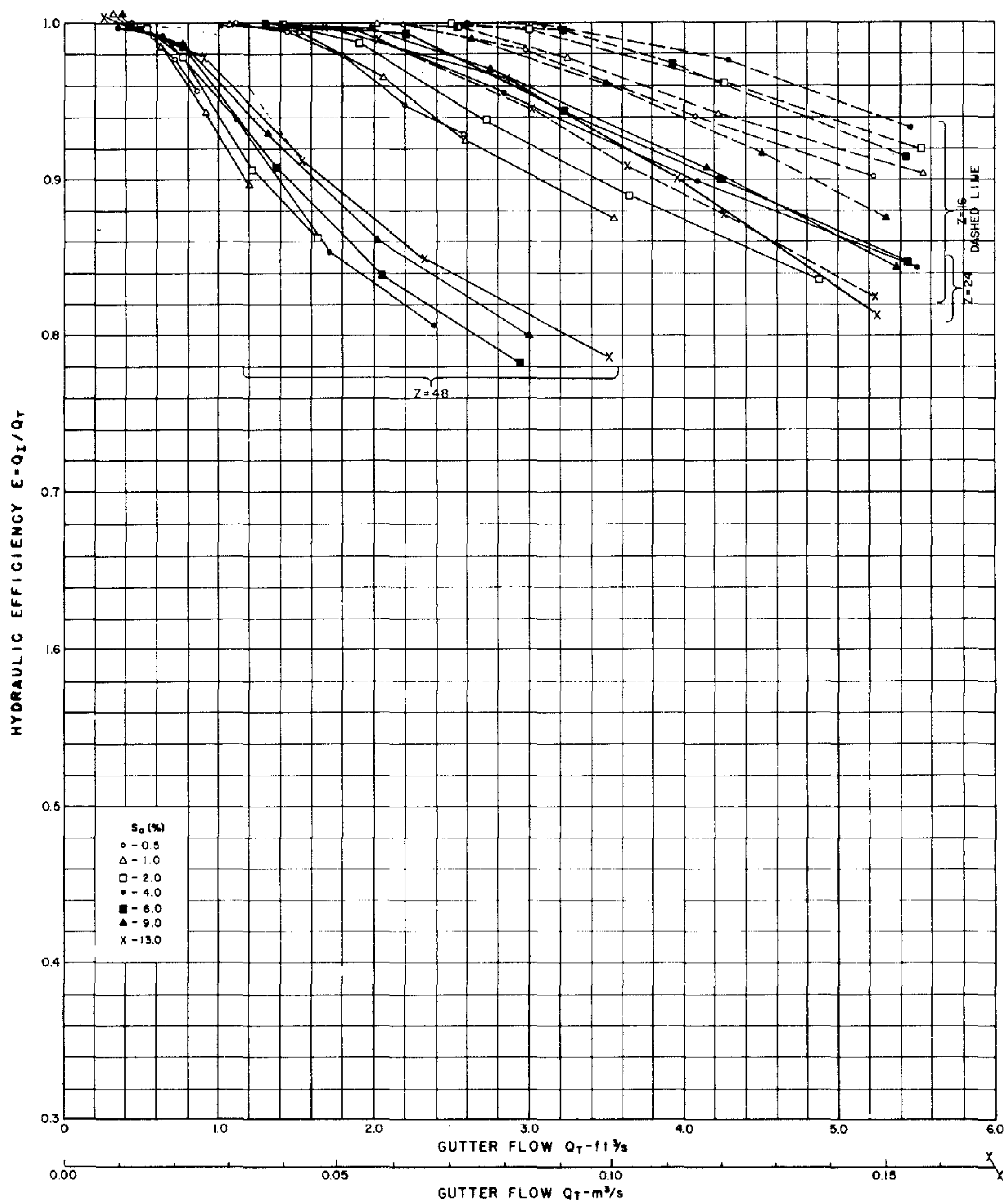


Figure 3-2. - Hydraulic efficiency vs. gutter flow, 3.0 ft by 4.0 ft (0.91 m by 1.22 m) P - 1-7/8 - 4 grate.

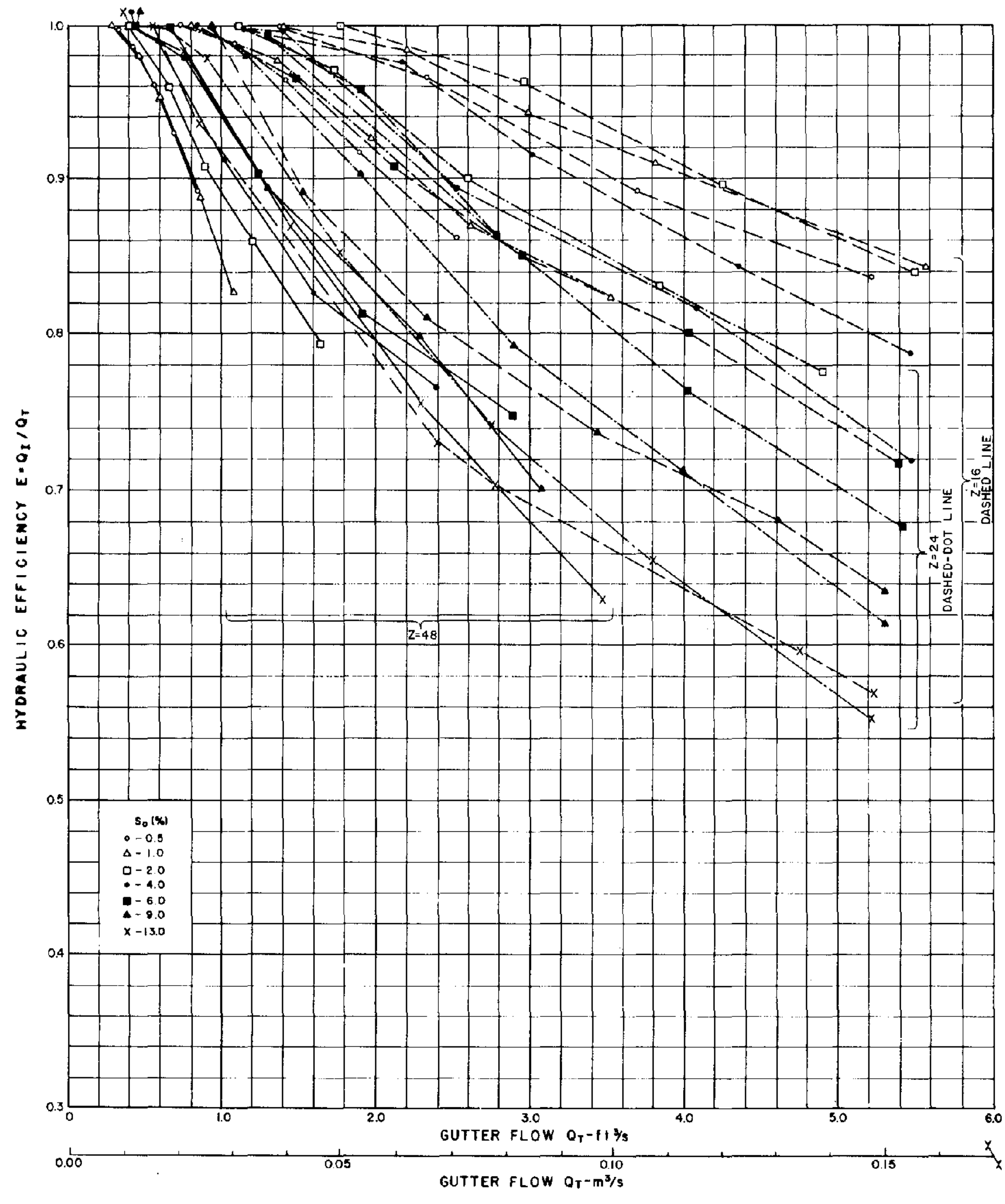


Figure 3-3. - Hydraulic efficiency vs. gutter flow, 3.0 ft by 2.0 ft (0.91 m by 0.61 m) P - 1-7/8 - 4 grate.

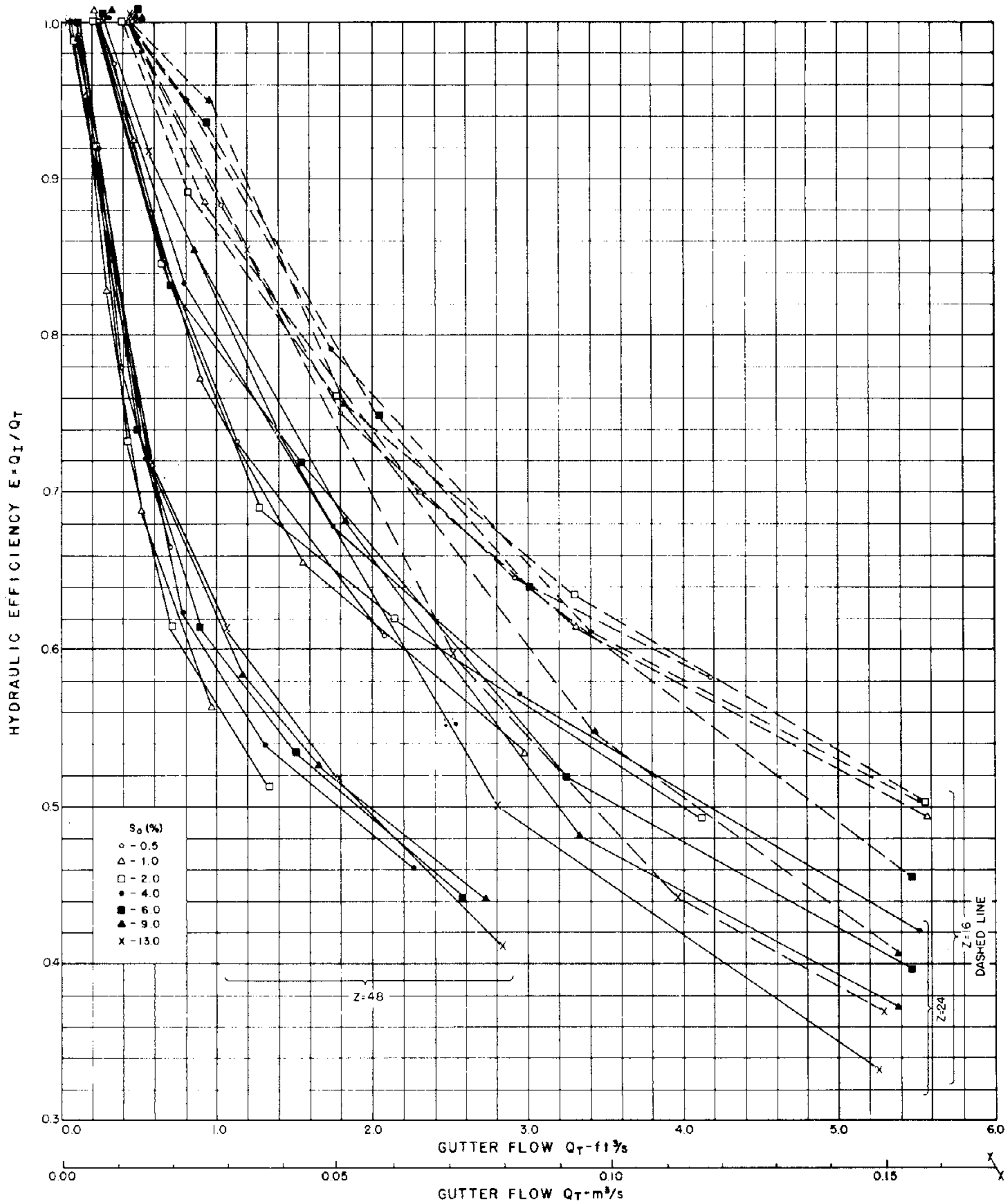


Figure 3-4. - Hydraulic efficiency vs. gutter flow, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) P - 1-7/8 - 4 grate.

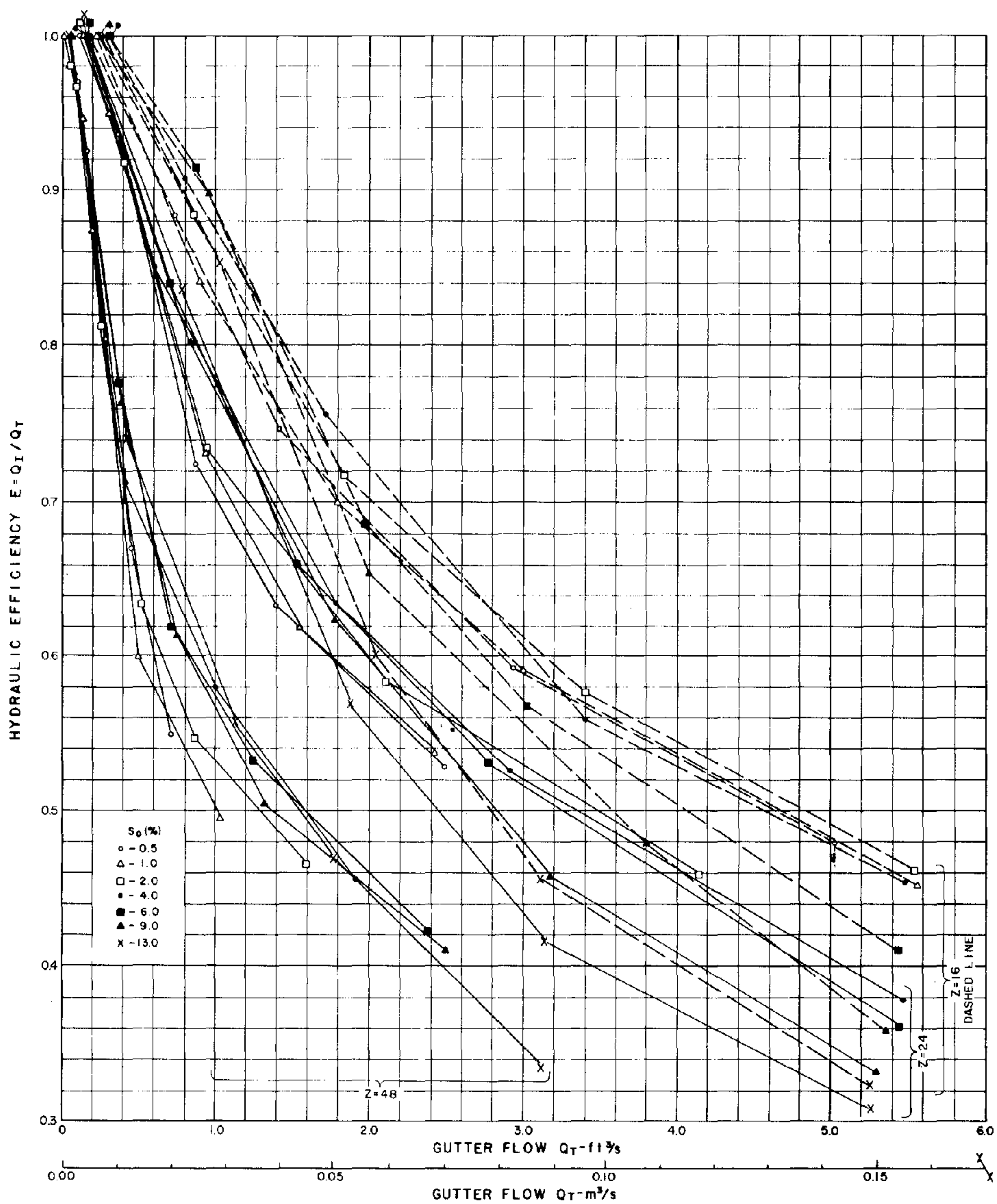


Figure 3-5. - Hydraulic efficiency vs. gutter flow, 1.25 ft by 2.0 ft (0.38 m by 0.61 m) P - 1-7/8 - 4 grate.

longitudinal slopes can be identified for a given size grate and cross slope condition. These are presented in table 3-2.

The maximum efficiency slopes identify the approximate longitudinal slope for a specific cross slope, 1/Z. When this longitudinal slope is exceeded the hydraulic efficiency decreases rapidly as a result of splashing over the transverse bars.

For the 1/Z = 1/48 cross slope, the P - 1-7/8 - 4 grate drops very little in efficiency as the longitudinal slope is increased. A weak flow layer develops on the grate, but the flow does not have the energy compared to the steeper cross slopes of 1/24 and 1/16. Figure 3-6 illustrates a 3 ft by 4 ft (0.91 m by 1.22 m) P - 1-7/8 - 4 grate at 13 percent longitudinal slope with 1/16 and 1/48 cross slopes.

Figures 3-7 through 3-10 show the relationship between measured width of spread, T', and hydraulic efficiency, E, for the four grate sizes tested. For the same width of spread, T', hydraulic efficiencies increase as the longitudinal slope is decreased.

Figures 3-11 through 3-22 present the 12 grate inlet capacity curves for the four P - 1-7/8 - 4 grate sizes and three cross slope conditions. The grate inlet capacity curves clearly illustrate, by the change in direction of efficiency curves, the start of the splash or flow layer, as longitudinal slope, S_0, is increased. These curves further verify the maximum efficiency longitudinal slopes identified in table 3-2.

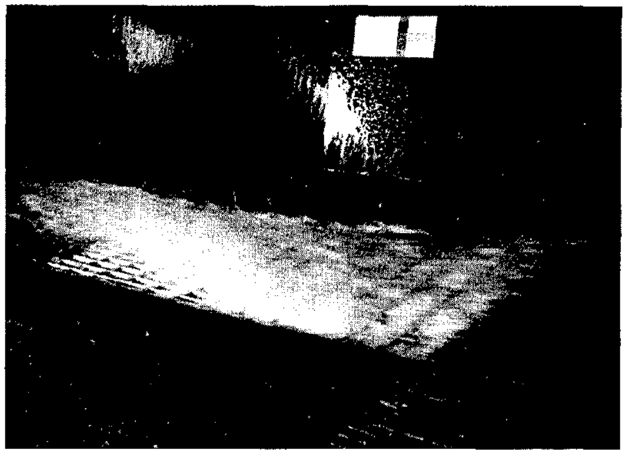
Summary

The P - 1-7/8 - 4 grates have bicycle safety characteristics as discussed in chapter 3 of volume 1. It also is a hydraulic efficient grate at or below the specific longitudinal and cross slopes identified in table 3-2. For steep cross slopes, 1/Z = 1/16 or 1/24, the P - 1-7/8 - 4 grate does not perform well above $S_0 \doteq 4$ percent. For the cross slope, 1/Z = 1/48, the longitudinal slope should not exceed 6 to 13 percent.

Figures 3-23 through 3-25 show the performance of the six grate sizes (including the two sizes in chapter 11 of volume 1) for a given width of spread, T', as the longitudinal slope, S_0, varies. As stated in chapter 2, the width of spread, T', chosen for each cross slope, is near the maximum tested on the hydraulic test facility. To maintain the same width of spread, T', the gutter flow, Q_T, is increased as the longitudinal slope is increased from 0.5 percent to 13 percent. There is a resultant decrease in the hydraulic efficiency of the grates.

Table 3-2. - *Maximum efficiency longitudinal slopes for P - 1-7/8 - 4 grates*

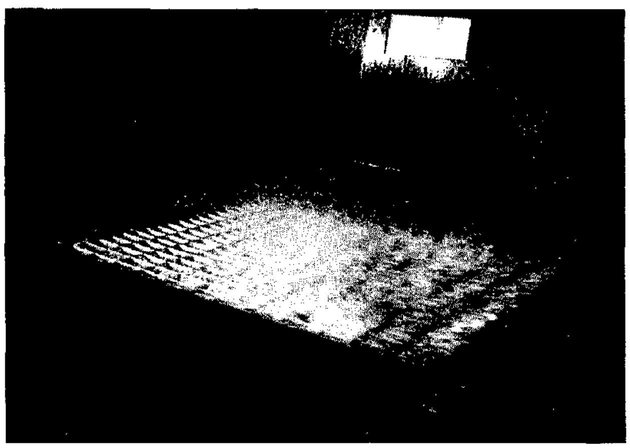
	3.0 by 4.0 ft (0.91 by 1.22 m)	3.0 by 2.0 ft (0.91 by 0.61 m)	1.25 by 2.67 ft (0.38 by 0.81 m)	1.25 by 2.0 ft (0.38 by 0.61 m)
1/Z = 1/16	4%	2%	3%	2%
1/Z = 1/24	6-13%	3%	4%	4%
1/Z = 1/48	>13%	9-13%	9-13%	6-13%



a. $Z = 16$ $E = 82.4\%$

$Q_T = 5.24$ ft^3/s (0.148 m^3/s) $T' = 4.4$ ft (1.34 m)

Photo 186-8A



b. $Z = 48$ $E = 78.6\%$

$Q_T = 3.50$ ft^3/s (0.099 m^3/s) $T' = 7.7$ ft (2.35 m)

Photo 186-19A

Figure 3-6. - Development of flow layer on P - 1-7/8 - 4 grate, $S_0 = 13\%$.

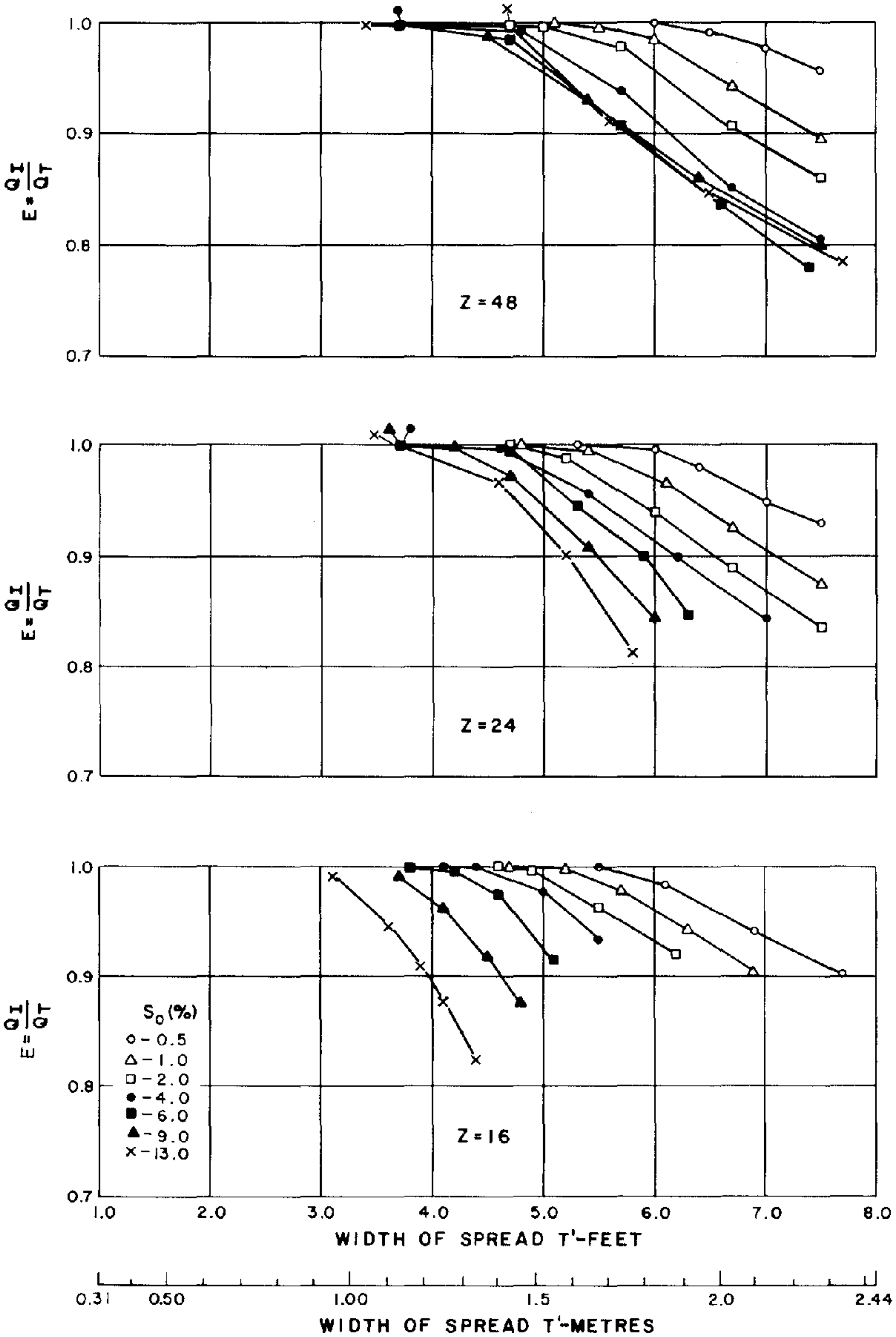


Figure 3-7. - Hydraulic efficiency vs. width of spread
3.0 ft by 4.0 ft (0.91 m by 1.22 m)
P - 1-7/8 - 4 grate.

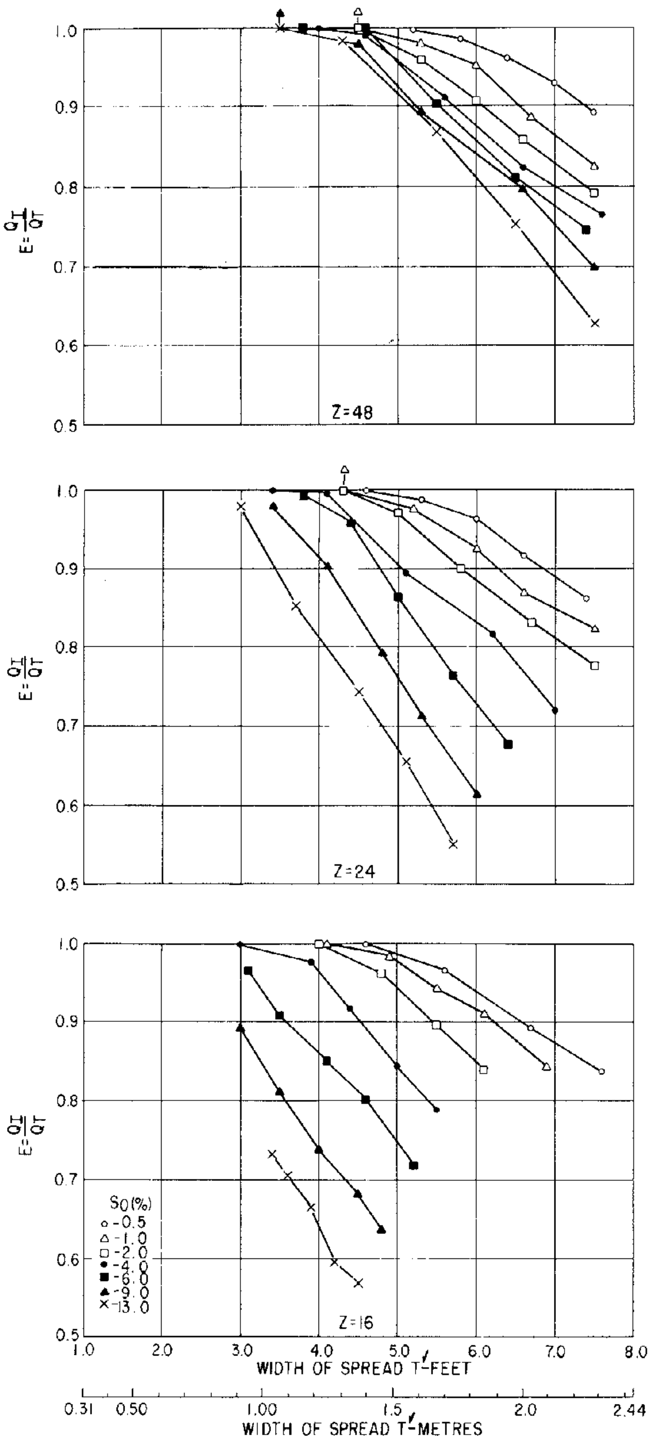


Figure 3-8. - Hydraulic efficiency vs. width of spread 3.0 ft by 2.0 ft (0.91 m by 0.61 m) P - 1-7/8 - 4 grate.

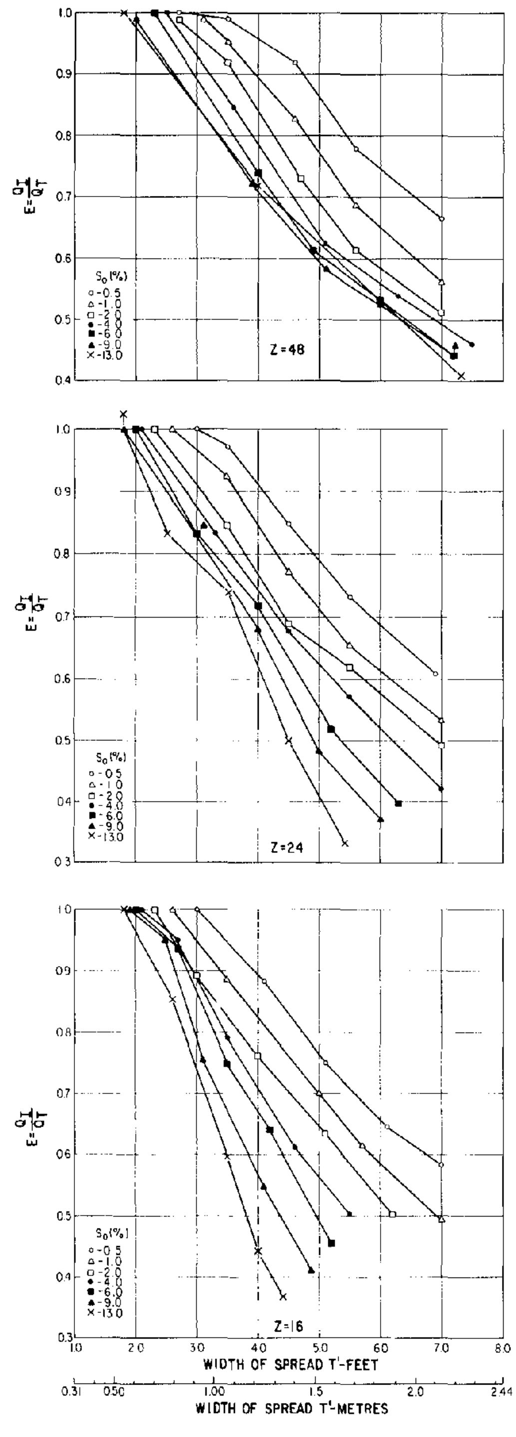


Figure 3-9. - Hydraulic efficiency vs. width of spread 1.25 ft by 2.67 ft (0.38 m by 0.81 m) P - 1-7/8 - 4 grate.

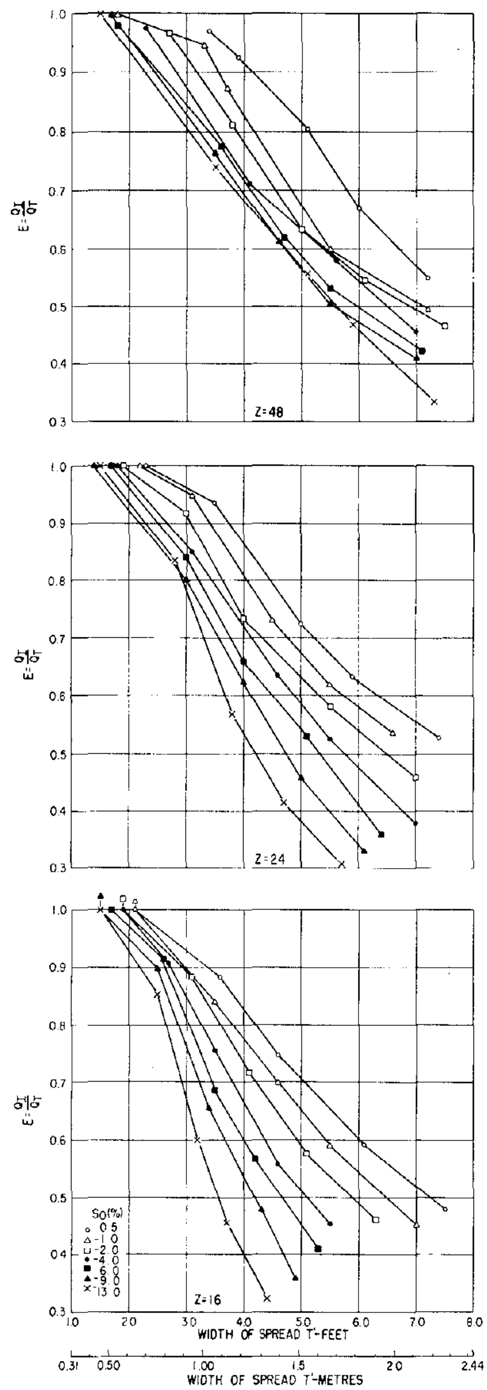


Figure 3-10. - Hydraulic efficiency vs. width of spread 1.25 ft by 2.0 ft (0.38 m by 0.61 m) P - 1-7/8 - 4 grate.

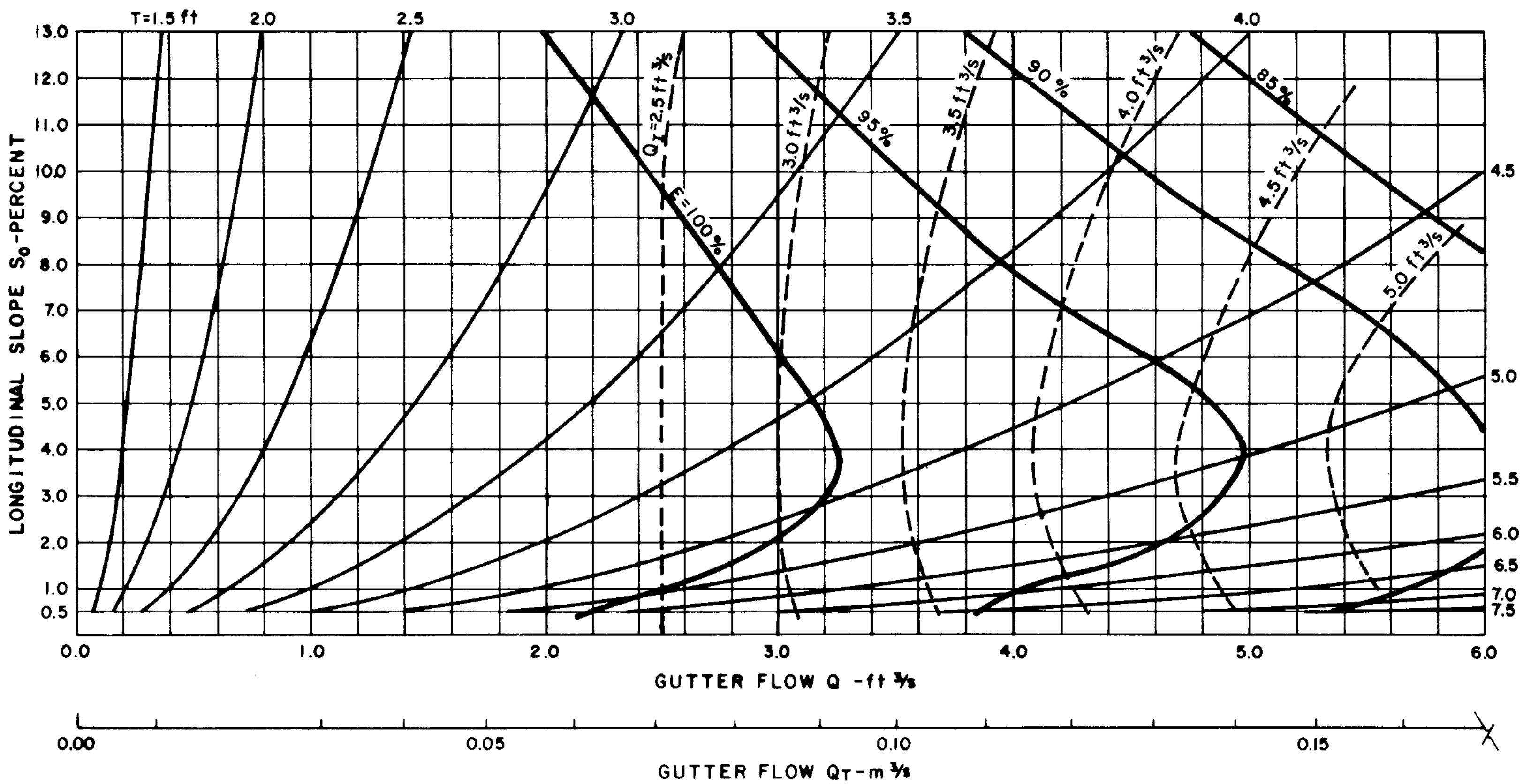


Figure 3-11. - Grate inlet capacity curves, 3.0 ft by 4.0 ft (0.91 m by 1.22 m) P - 1-7/8 - 4 grate, Z = 16.

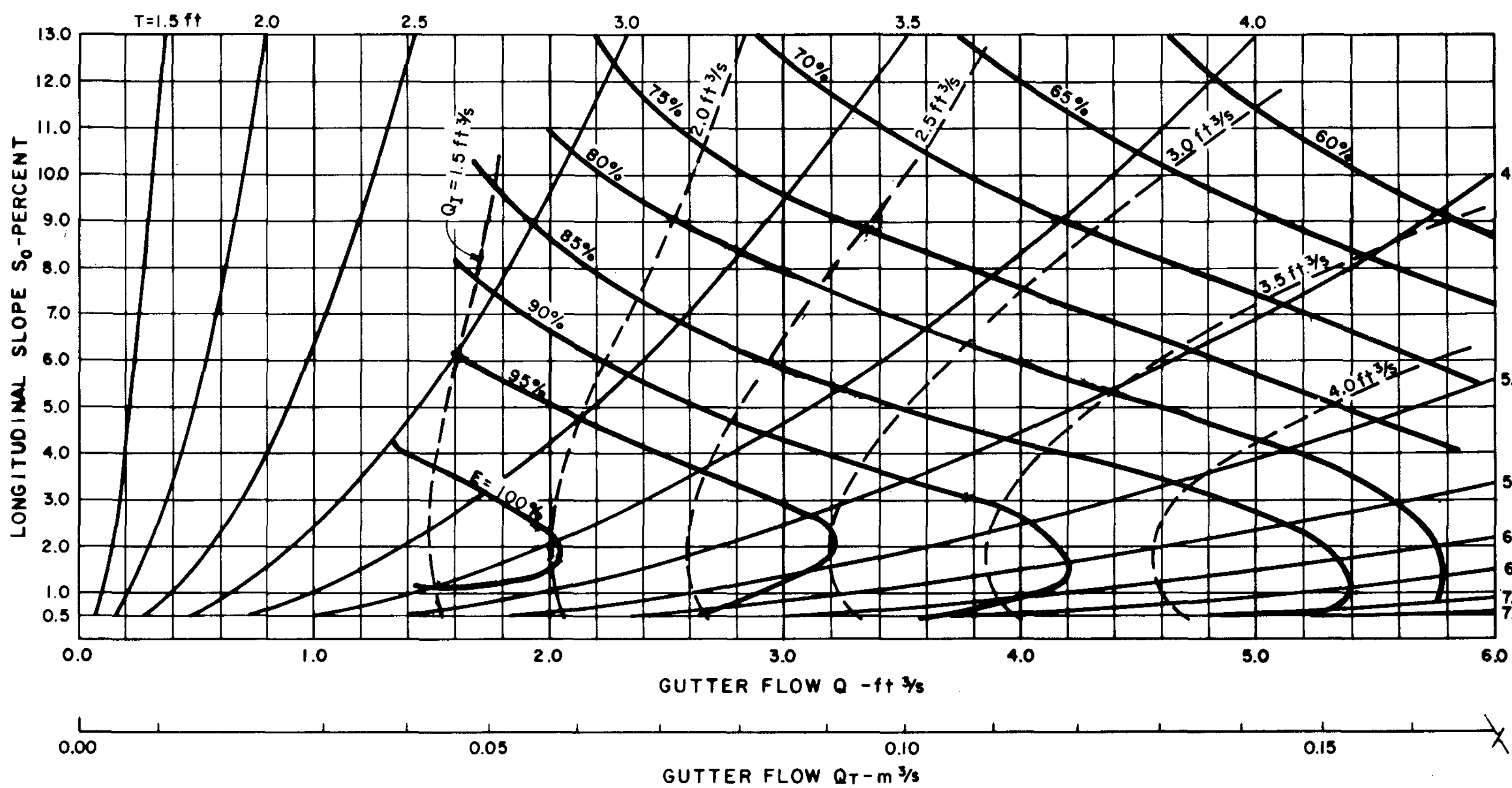


Figure 3-12. - Grate inlet capacity curves, 3.0 ft by 2.0 ft (0.91 m by 0.61 m) P - 1-7/8 - 4 grate, Z = 16.

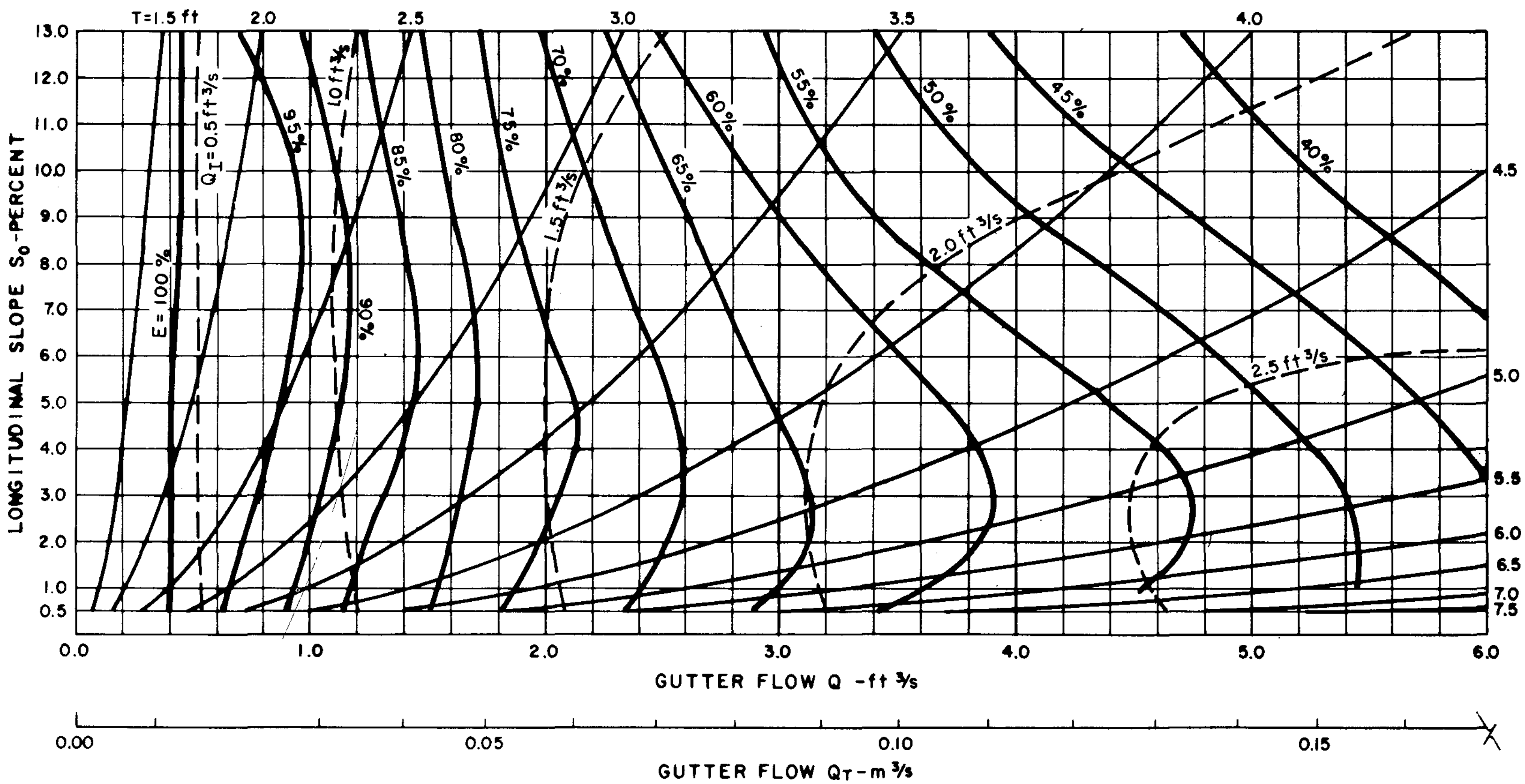


Figure 3-13. - Grate inlet capacity curves, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) P - 1-7/8 - 4 grate, Z = 16.

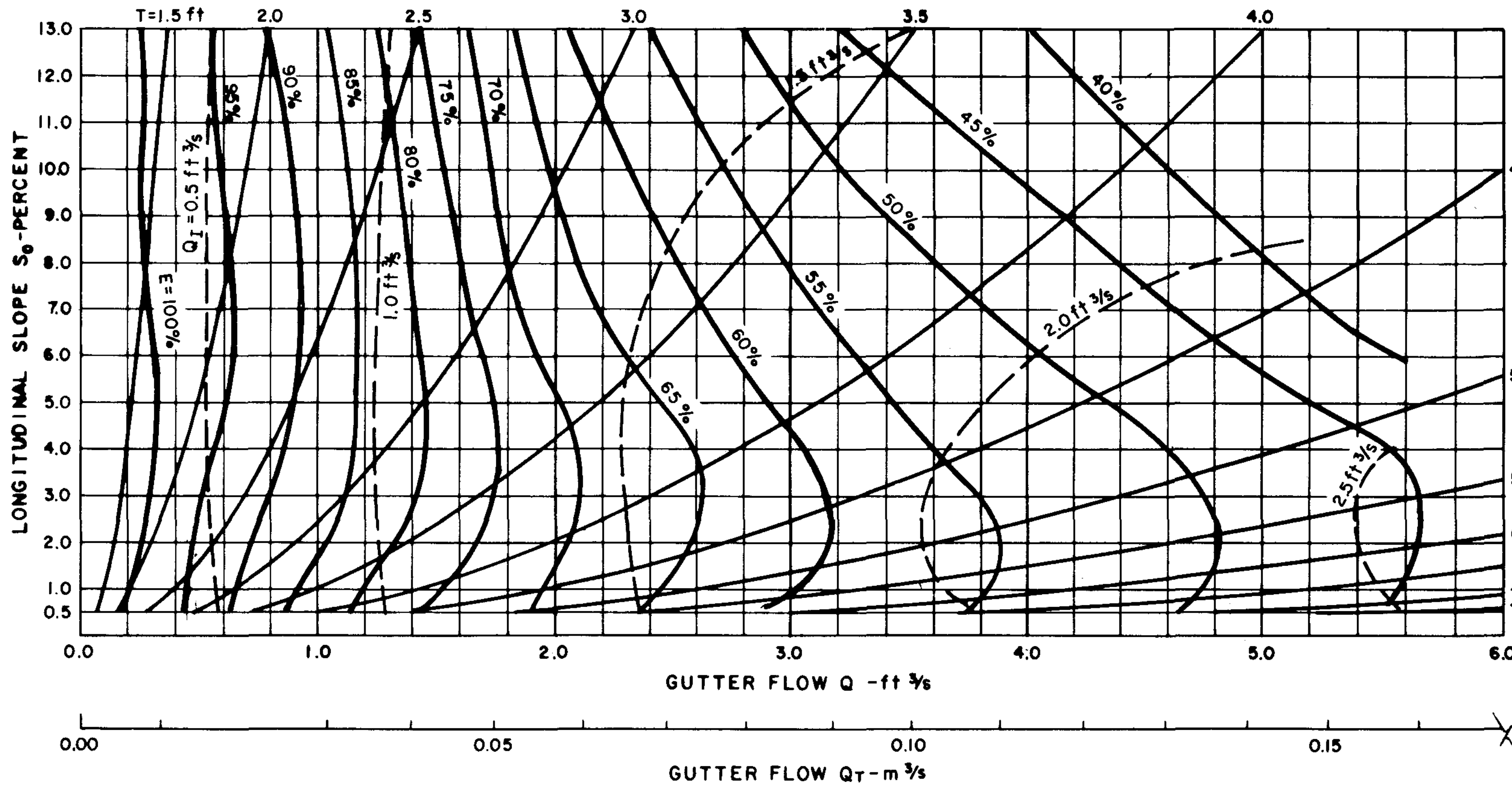


Figure 3-14. - Grate inlet capacity curves, 1.25 ft by 2.0 ft (0.38 m by 0.61 m)
P - 1-7/8 - 4 grate, Z = 16.

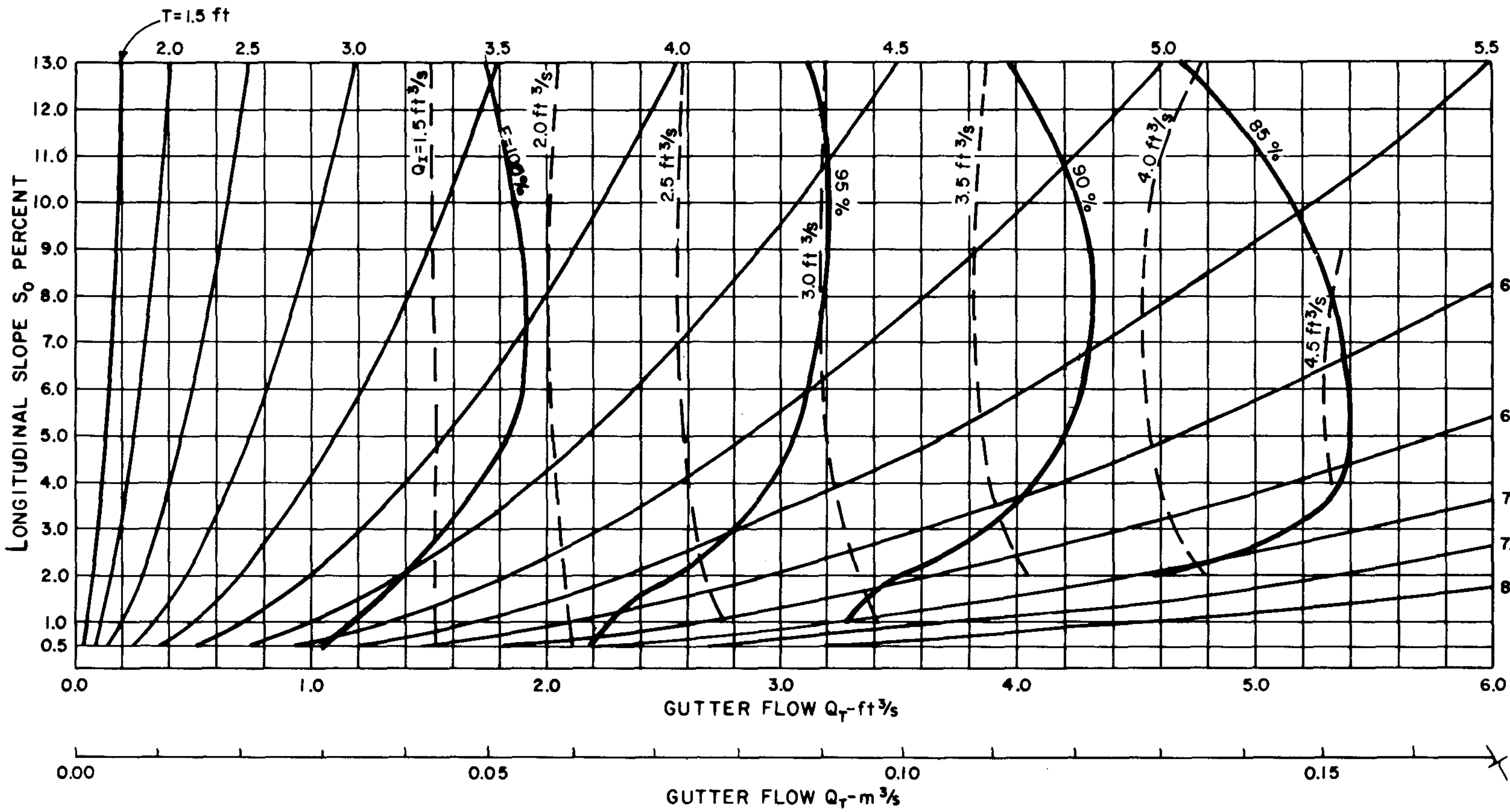


Figure 3-15. - Grate inlet capacity curves, 3.0 ft by 4.0 ft (0.91 m by 1.22 m)
P - 1-7/8 - 4 grate, Z = 24.

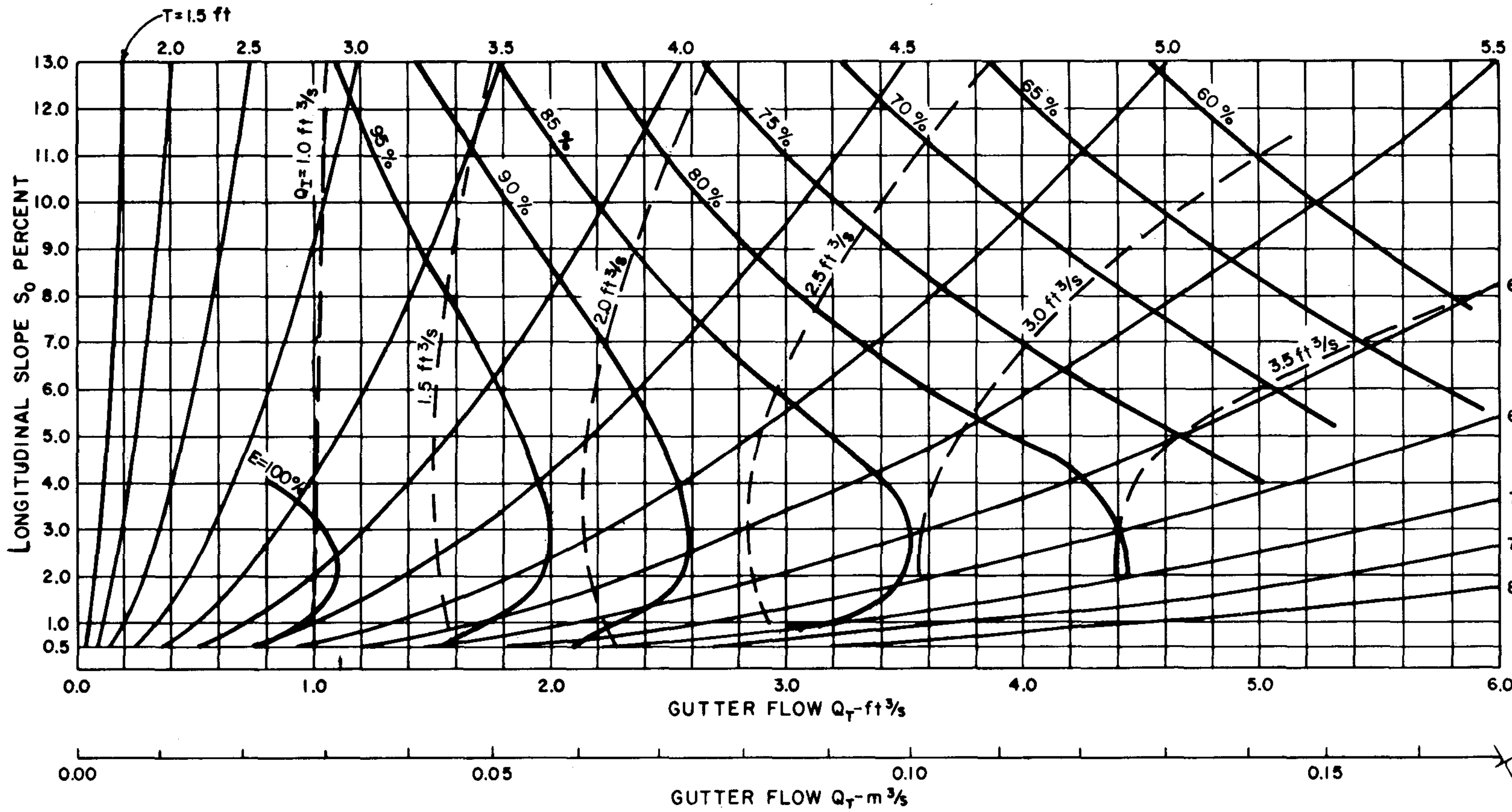


Figure 3-16. - Grate inlet capacity curves, 3.0 ft by 2.0 ft (0.91 m by 0.61 m)
P - 1-7/8 - 4 grate, Z = 24.

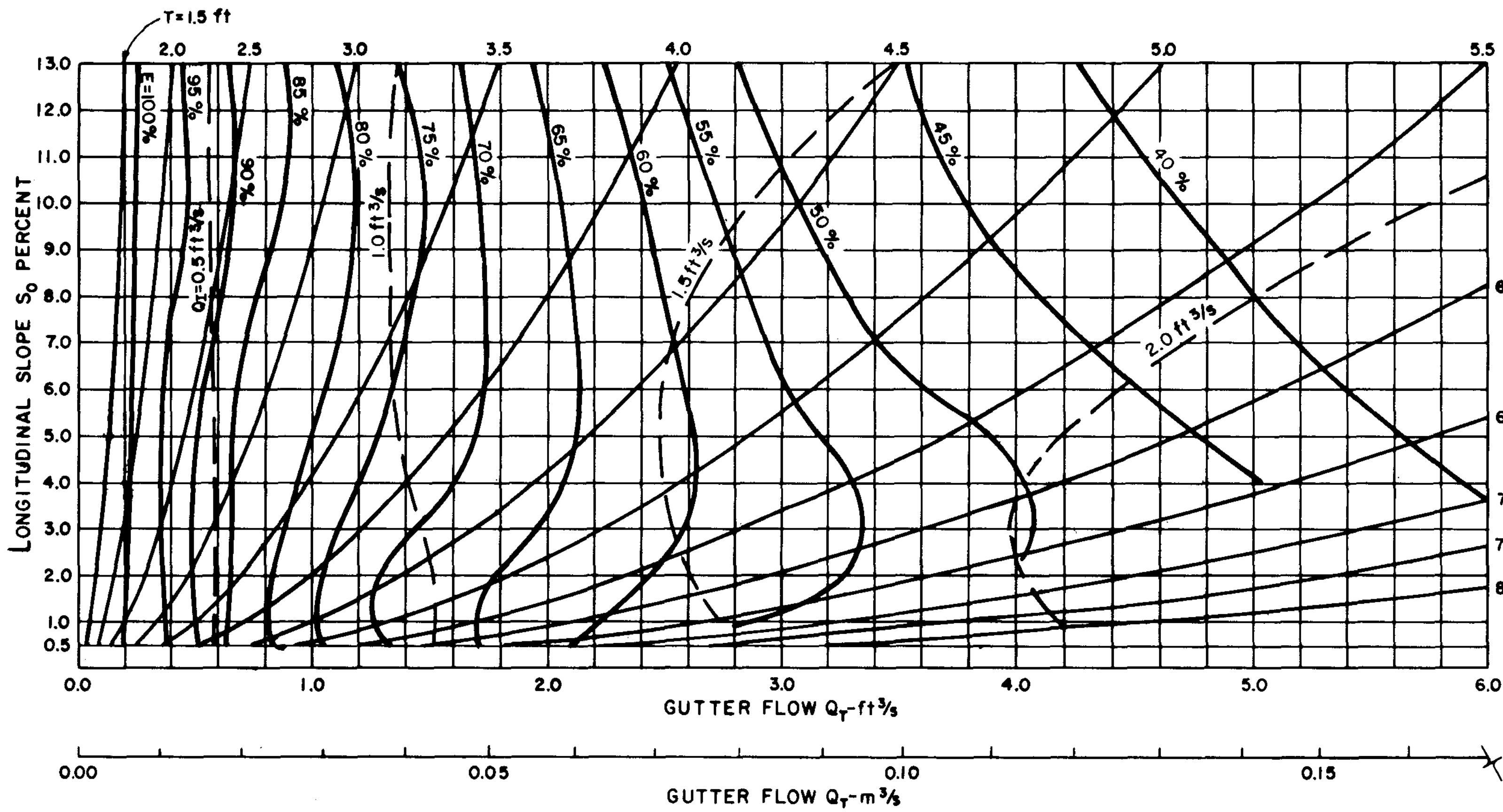


Figure 3-17. - Grate inlet capacity curves, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) P - 1-7/8 - 4 grate, Z = 24.

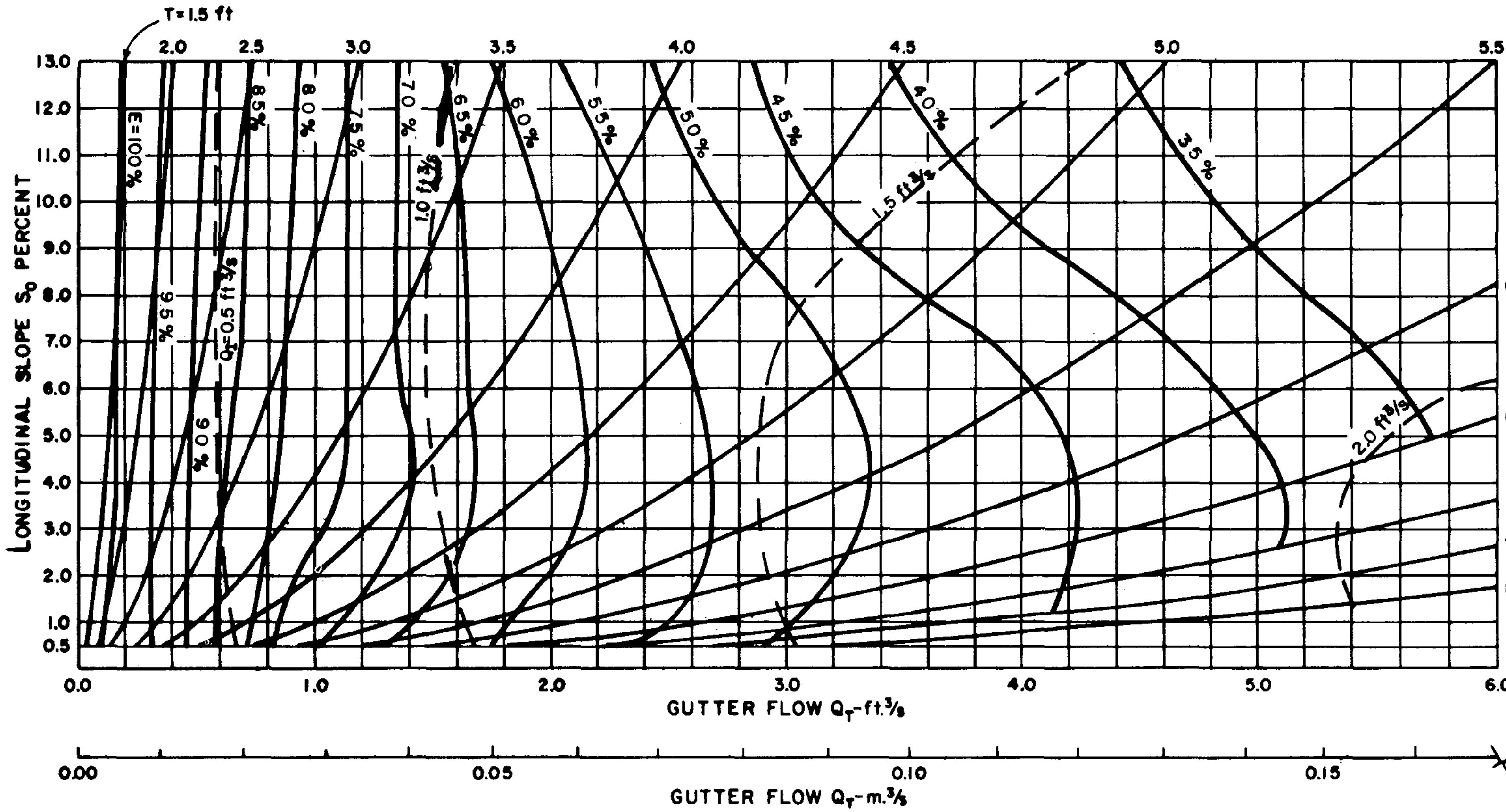


Figure 3-18. - Grate inlet capacity curves, 1.25 ft by 2.0 ft (0.38 m by 0.61 m)
P - 1-7/8 - 4 grate, Z = 24.

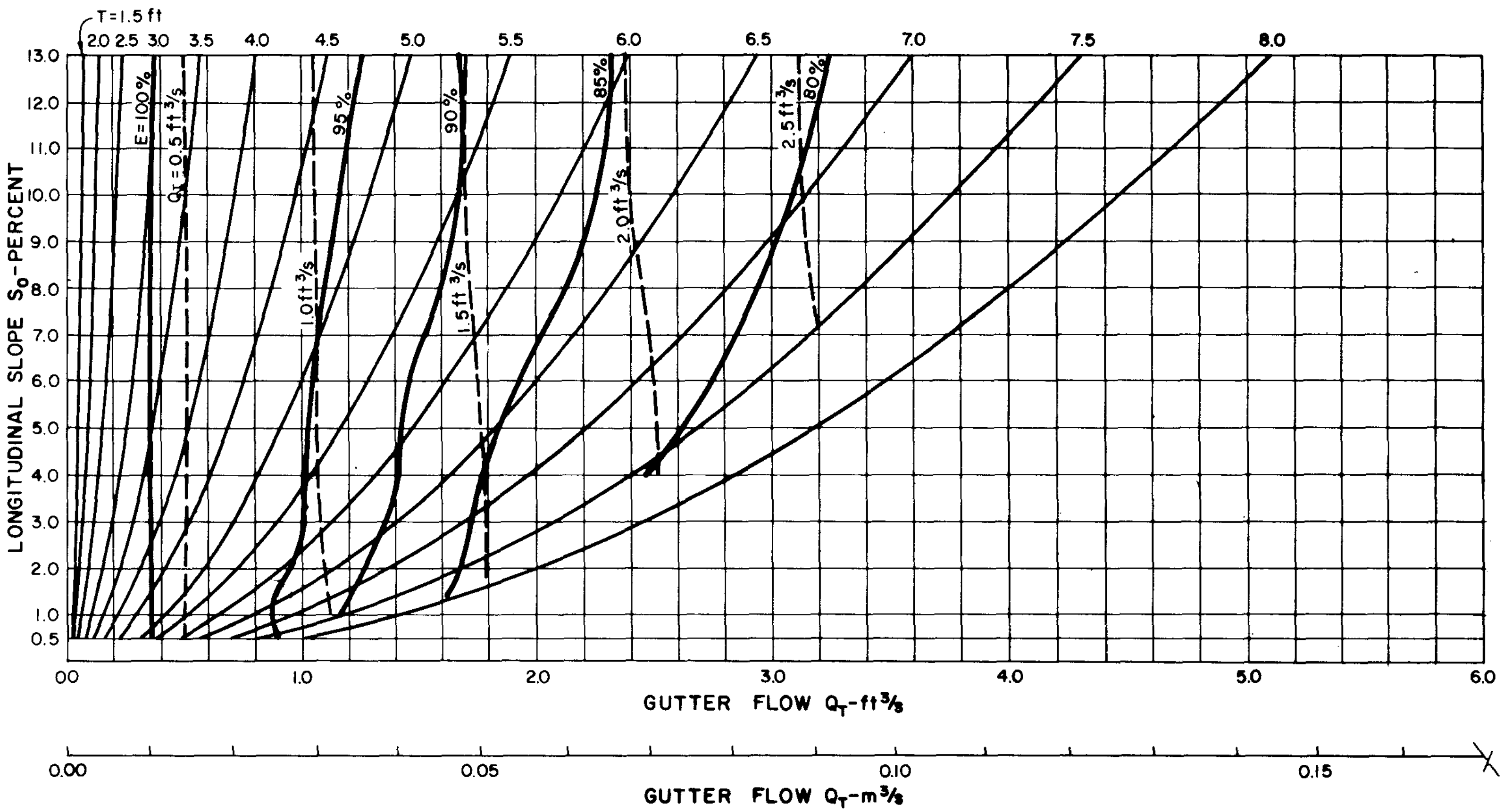


Figure 3-19. - Grate inlet capacity curves, 3.0 ft by 4.0 ft (0.91 m by 1.22 m) P - 1-7/8 - 4 grate, Z = 48.

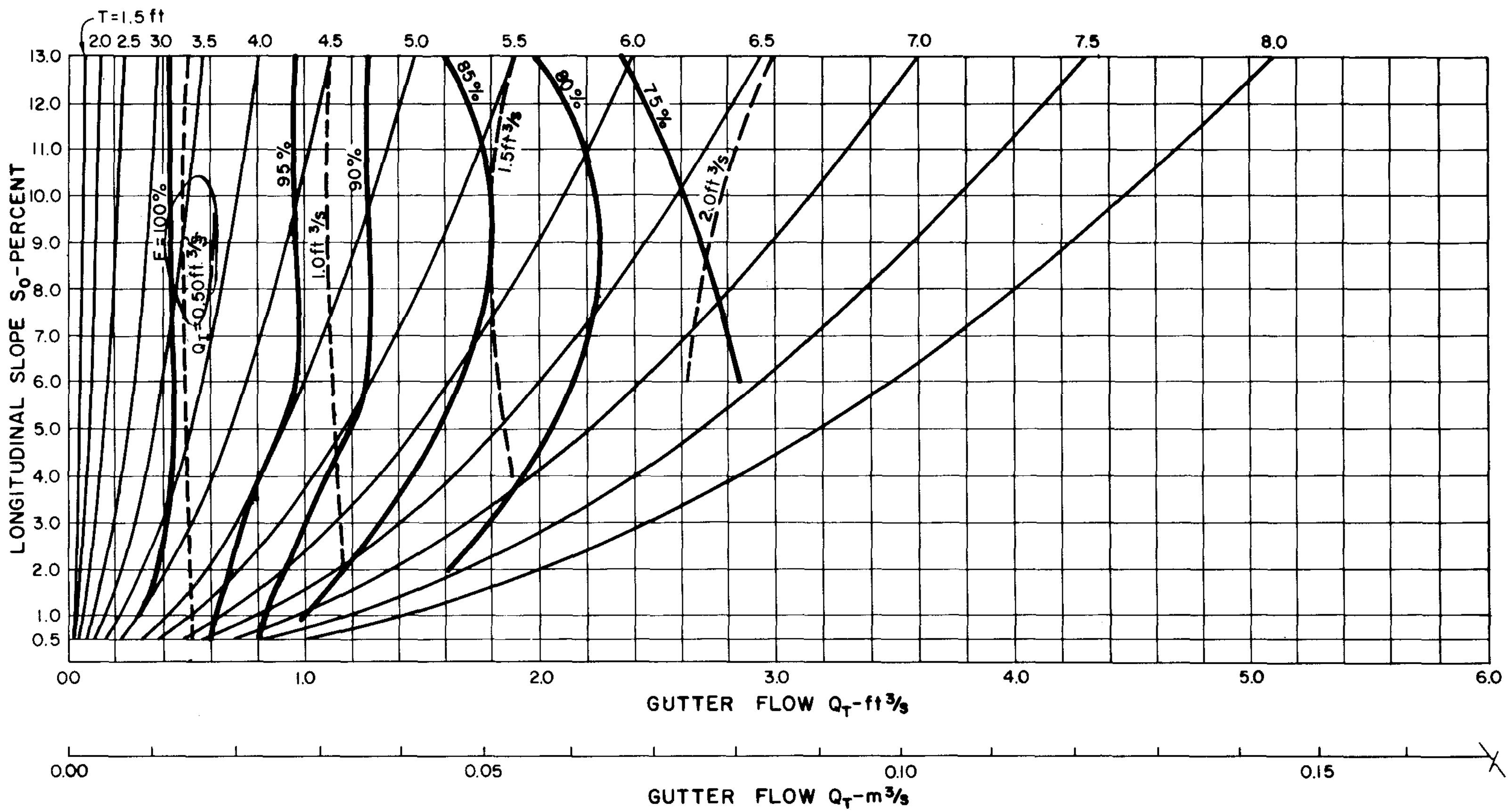


Figure 3-20. - Grate inlet capacity curves, 3.0 ft by 2.0 ft (0.91 m by 0.61 m)
P - 1-7/8 - 4 grate, Z = 48.

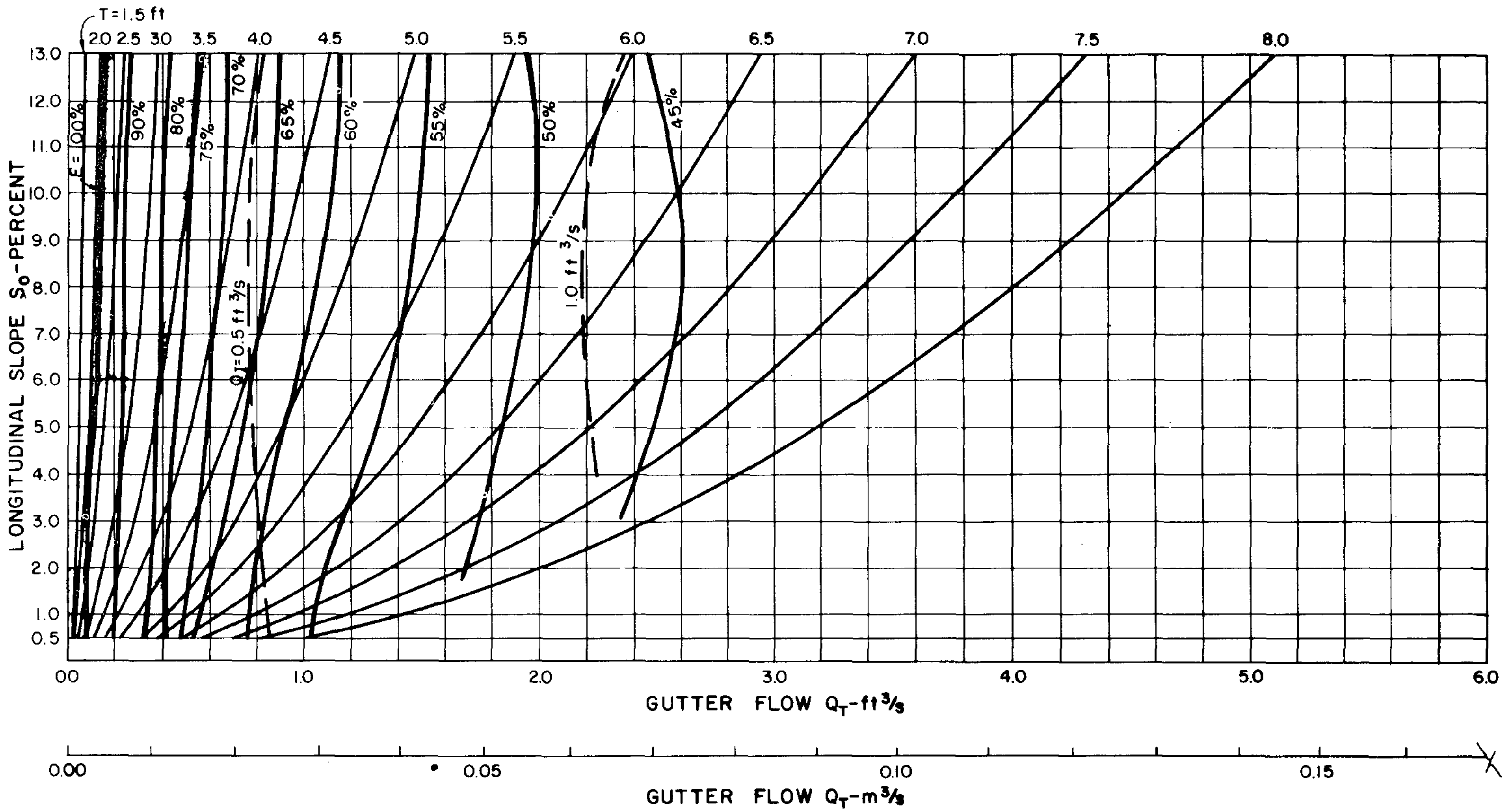


Figure 3-21. - Grate inlet capacity curves, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) P - 1-7/8 - 4 grate, Z = 48.

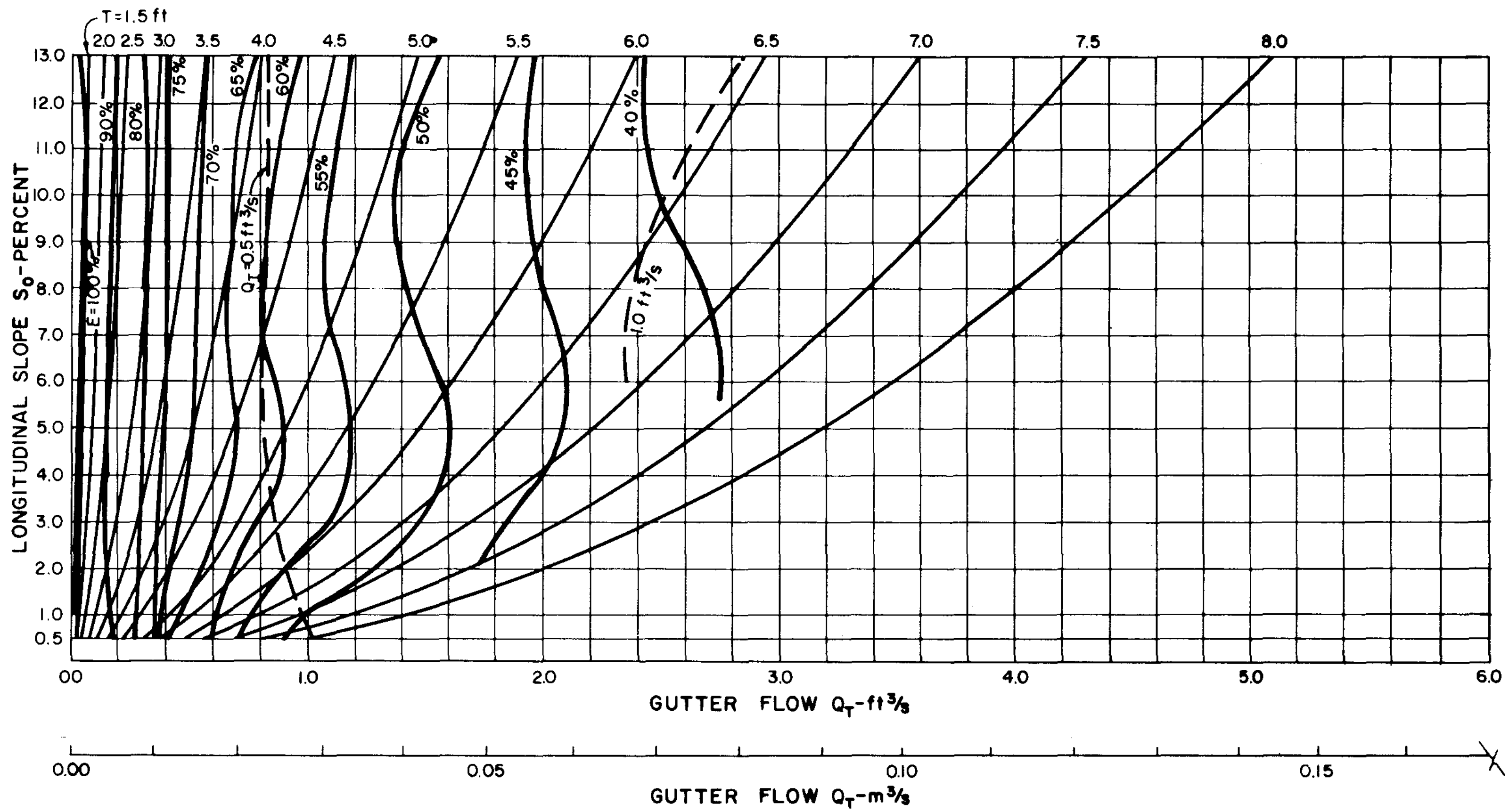


Figure 3-22. - Grate inlet capacity curves, 1.25 ft by 2.0 ft (0.38 m by 0.61 m) P - 1-7/8 - 4 grate, Z = 48.

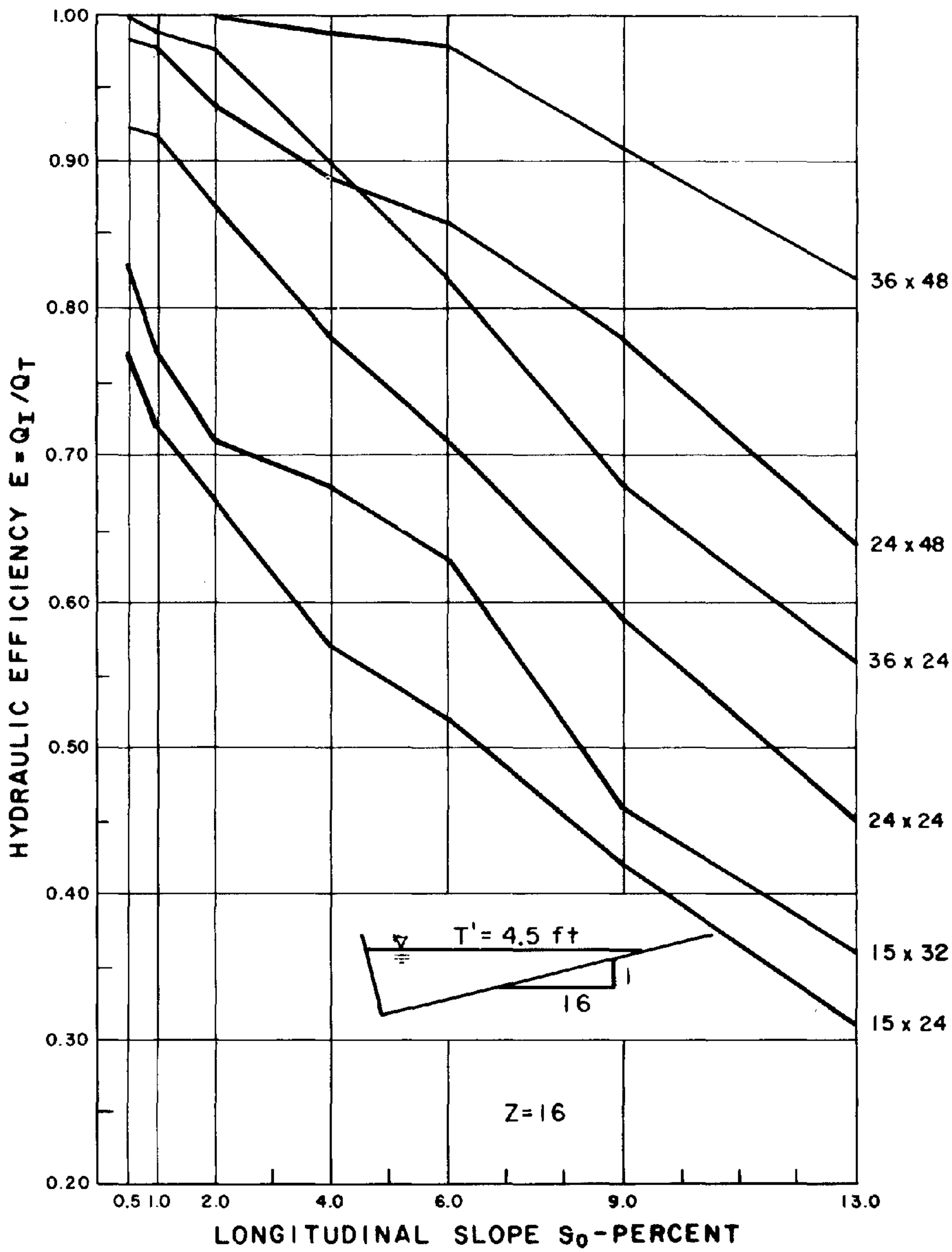


Figure 3-23. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, P - 1-7/8 - 4 grate, T' = 4.5 ft (1.37 m), Z = 16.

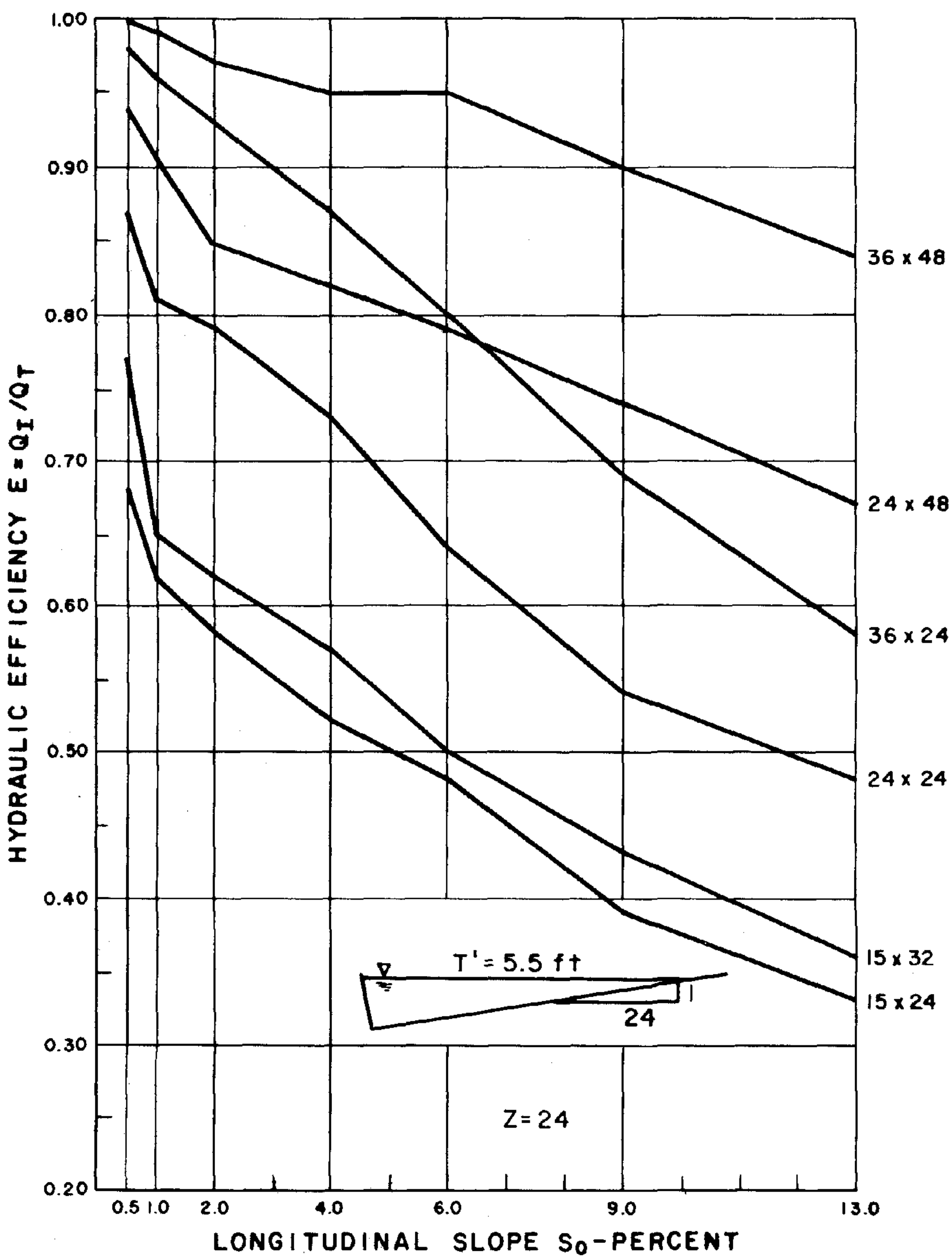


Figure 3-24. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, P - 1-7/8 - 4 grate, T' = 5.5 ft (1.68 m), Z = 24.

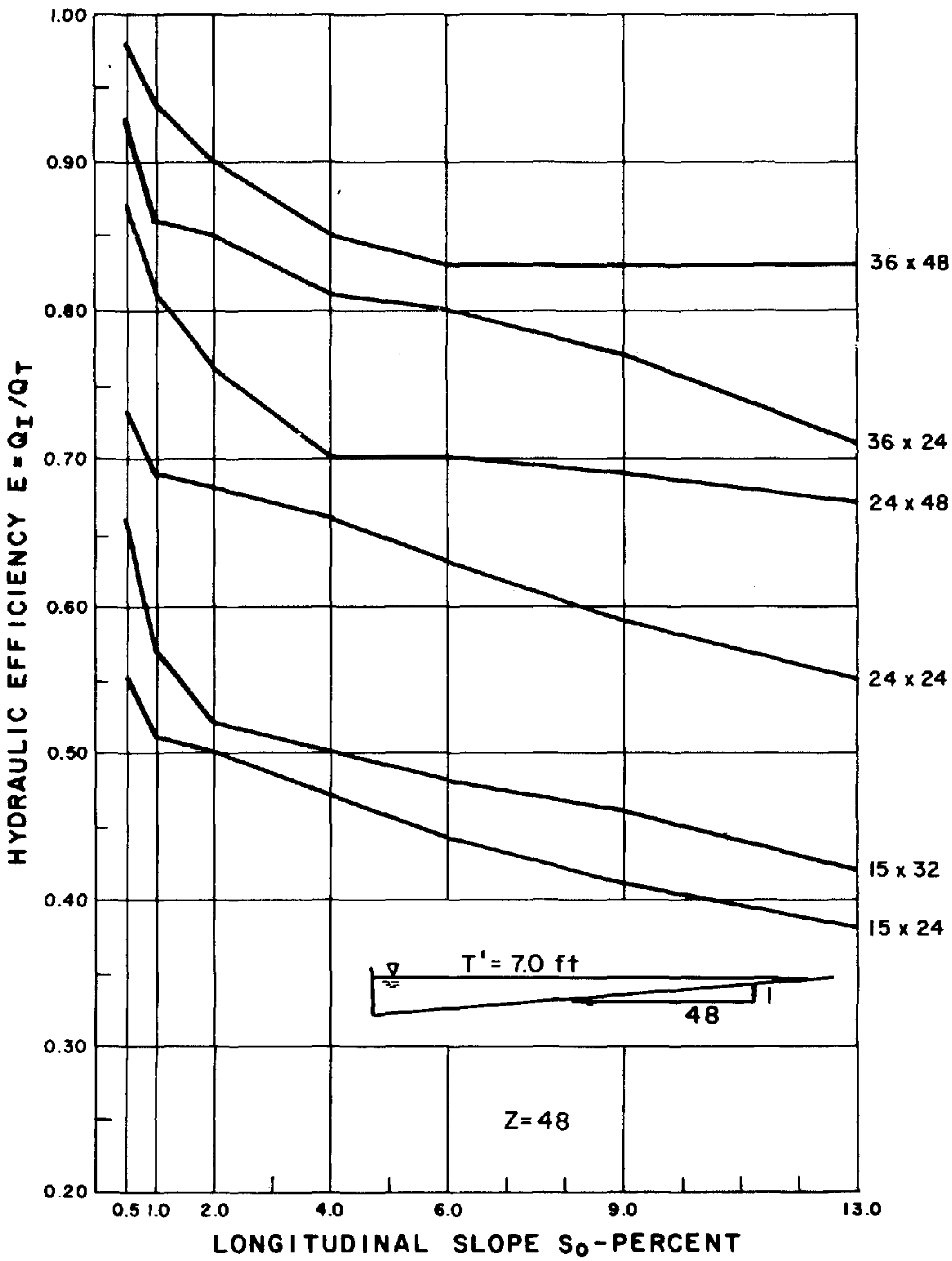


Figure 3-25. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, P - 1-7/8 - 4 grate, T' = 7.0 ft (2.13 m), Z = 48.

Figures 3-23 through 3-25 reveal several trends with the P - 1-7/8 - 4 grate.

1. For low longitudinal and cross slope conditions (S_0 less than 4 percent, or 1/Z = 1/48), the grate width is more important than length (the 3 ft by 2 ft (0.91 m by 0.61 m) grate is more efficient than the larger 2 ft by 4 ft (0.61 m by 1.22 m) grate).

2. Once splash conditions (S_0 greater than 4 percent, 1/Z = 1/16 or 1/24) occur on the grate, the length of grate becomes more important. Above S_0 = 4 percent on the 1/Z = 1/16 cross slope, the 2 ft by 4 ft (0.61 m by 1.22 m) grate size is more efficient than the 3 ft by 2 ft (0.91 m by 0.61 m) grate size.

Although the P - 1-7/8 - 4 grate has better debris handling characteristics than the P - 1-1/8 grate, it is not an efficient debris handling grate. (Chapter 11, volume 1.)

CHAPTER 4

THE CURVED VANE GRATE

CV - 3-1/4 - 4-1/4

This chapter contains the results of additional hydraulic tests conducted on four sizes of the curved vane grate (chapter 10, volume 1). The four grate sizes tested are shown in figure 4-1. It will be referred to in this chapter as the CV - 3-1/4 - 4-1/4. The longitudinal bars are placed approximately 3-1/4 in (83 mm) on centers and the curved vane bearing bars are approximately 4-1/4 in (108 mm) on centers.

Structural analysis of the curved vane section shown in figure 4-1 showed that for the widths of 1.25, 2.0, and 3.0 ft (0.38, 0.61, and 0.91 m), compressive and tensile stresses for the curved vane bar meet the allowable stresses for the ductile cast iron. The STR5 computer program described in volume 1 was used to analyze the curved vane grate. Ductile cast iron with an allowable tensile stress of 16,000 lb/in^2 (110 MPa) and an allowable compressive stress of 22,000 lb/in^2 (152 MPa) in the extreme fibers was used in the design.

Hydraulics

The hydraulic test results for the curved vane grate are shown in figures 4-2 through 4-5. For a specific gutter flow, Q_T, and longitudinal slope, S_0, the steeper cross slopes, 1/Z, produce higher hydraulic efficiencies. However on the 24 in (0.61 m) grate lengths at the steeper cross slopes and longitudinal slope (1/Z = 1/16, 1/24, and S_0 = 13 percent) the hydraulic efficiencies at the two cross slopes are nearly the same for the same grate sizes at large discharges (note figures 4-3 and 4-5). For both the 1.25 ft and 3 ft (0.38 m and 0.91 m) wide grates, the longer lengths of grate are more efficient for the same gutter flow conditions due to the added side flow and larger surface area. However, for a given surface area, the width of the CV - 3-1/4 - 4-1/4 grate is more important than its length. As with the other two grates tested the 3 ft by 2 ft (0.91 m by 0.61 m) size of the grate is more efficient than the larger 2 ft by 4 ft (0.61 m by 1.22 m) size (figure 4-3 of this volume and figure 10-2 of volume 1).

The transverse curved vane bars of the CV - 3-1/4 - 4-1/4 grate were very efficient for the majority of the roadway conditions tested. The curved vane bars capture the gutter flow along the width of the bars and direct it vertically into the catch basin. It is only at the high-energy gutter flow conditions that the curved vane bars

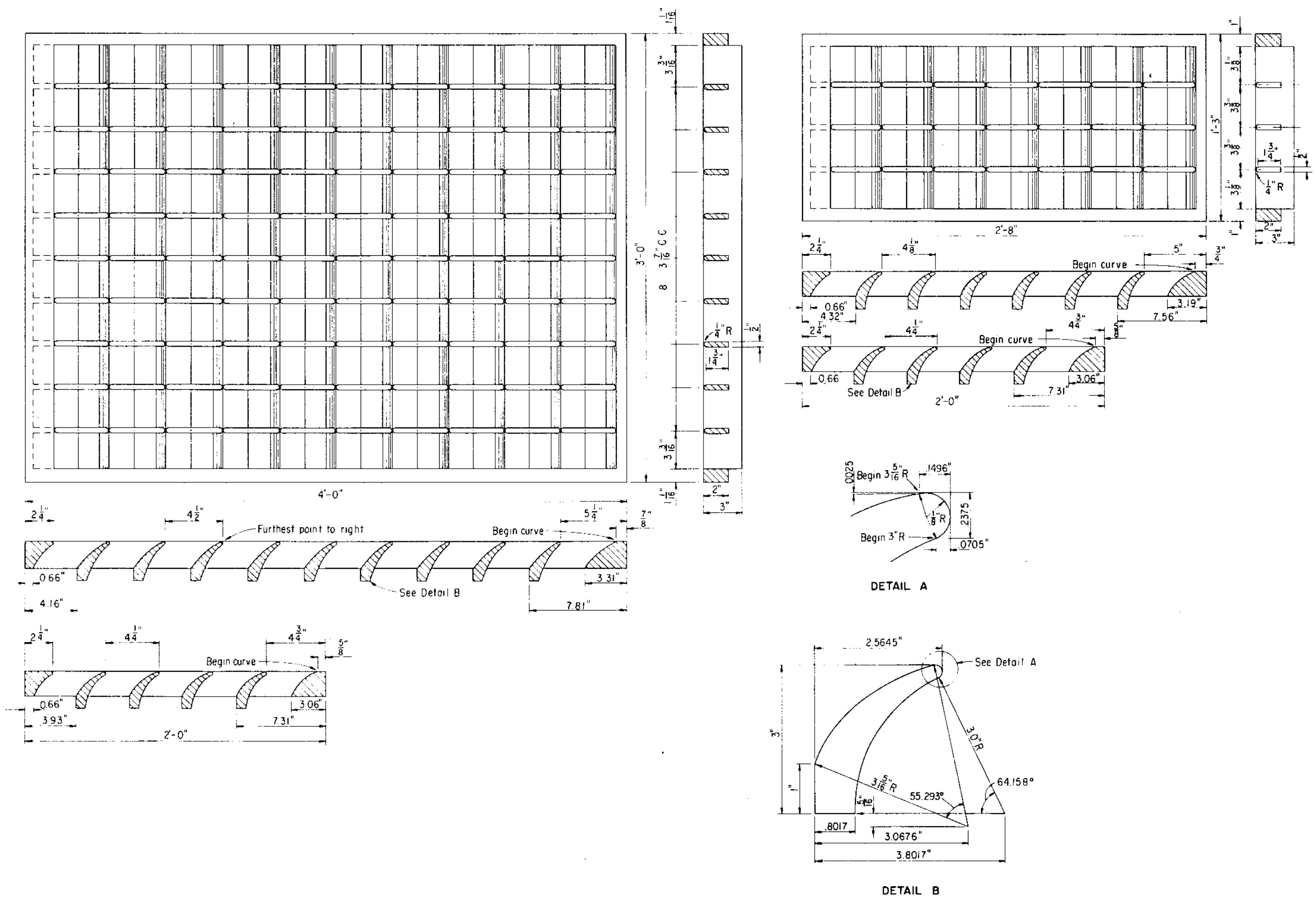


Figure 4-1. - Curved vane, CV - 3-1/4 - 4-1/4 grate.

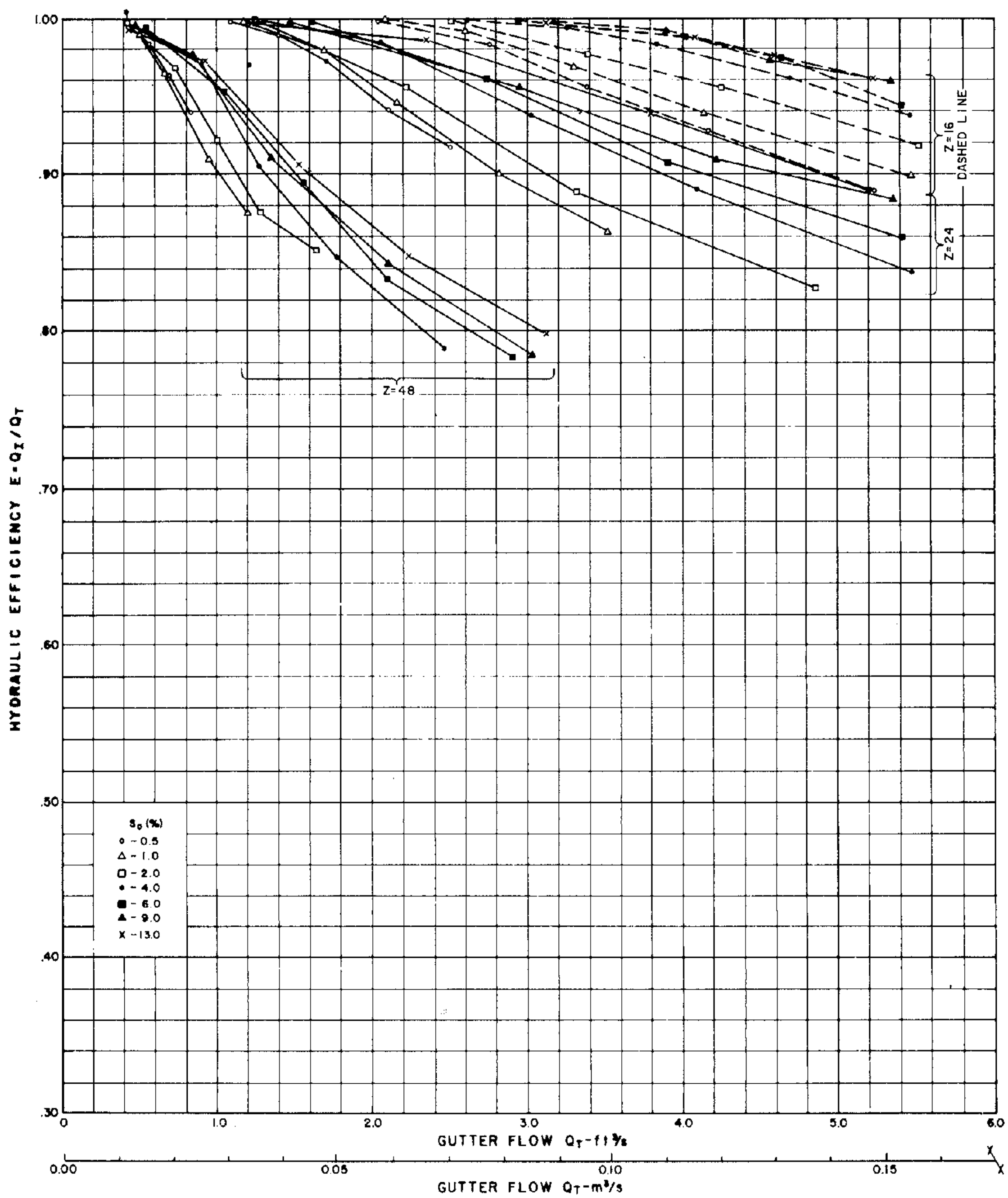


Figure 4-2. - Hydraulic efficiency vs. gutter flow, 3.0 ft by 4.0 ft (0.91 m by 1.22 m) CV - 3-1/4 - 4-1/4 grate.

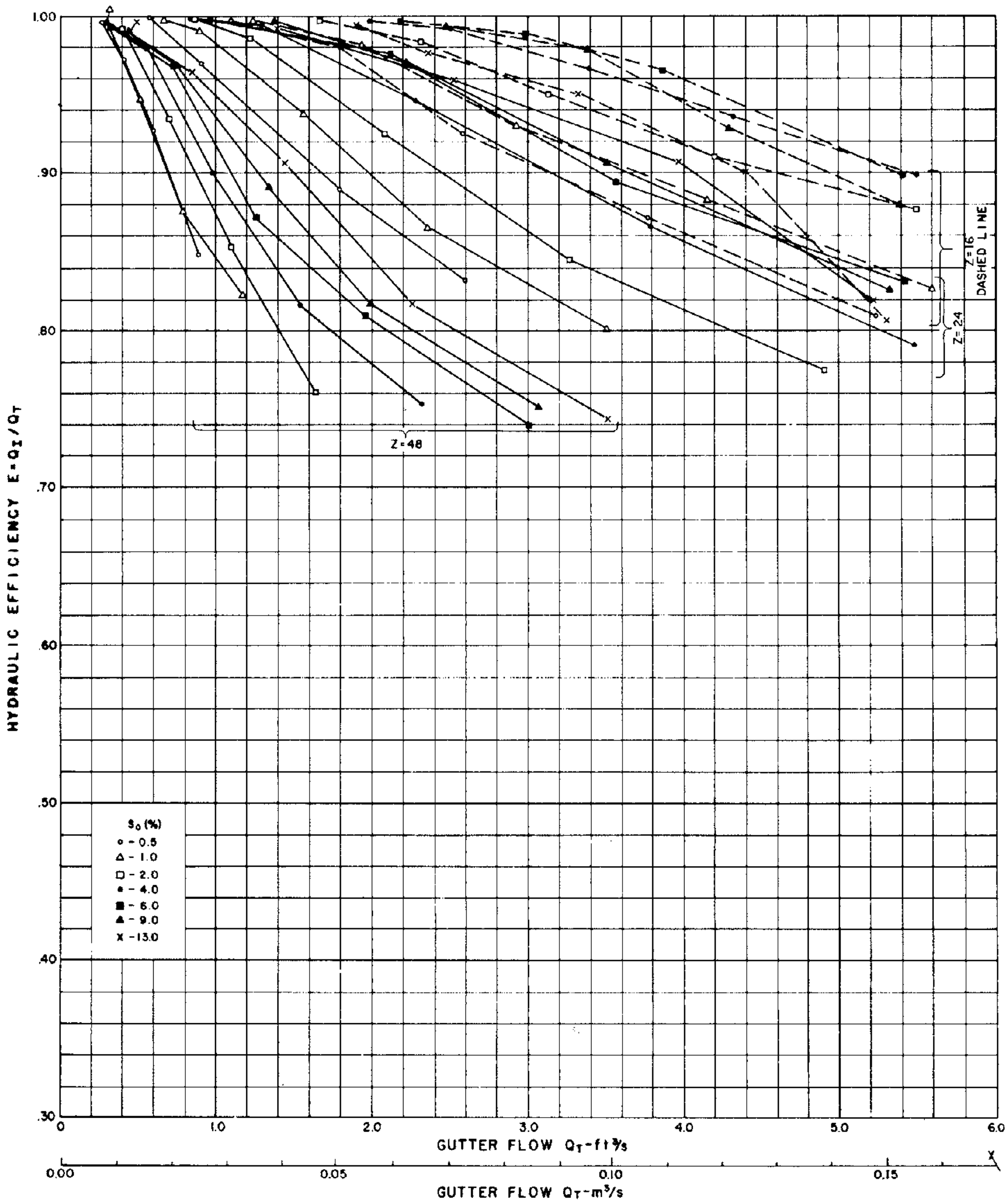


Figure 4-3. - Hydraulic efficiency vs. gutter flow, 3.0 ft by 2.0 ft (0.91 m by 0.61 m) CV - 3-1/4 - 4-1/4 grate.

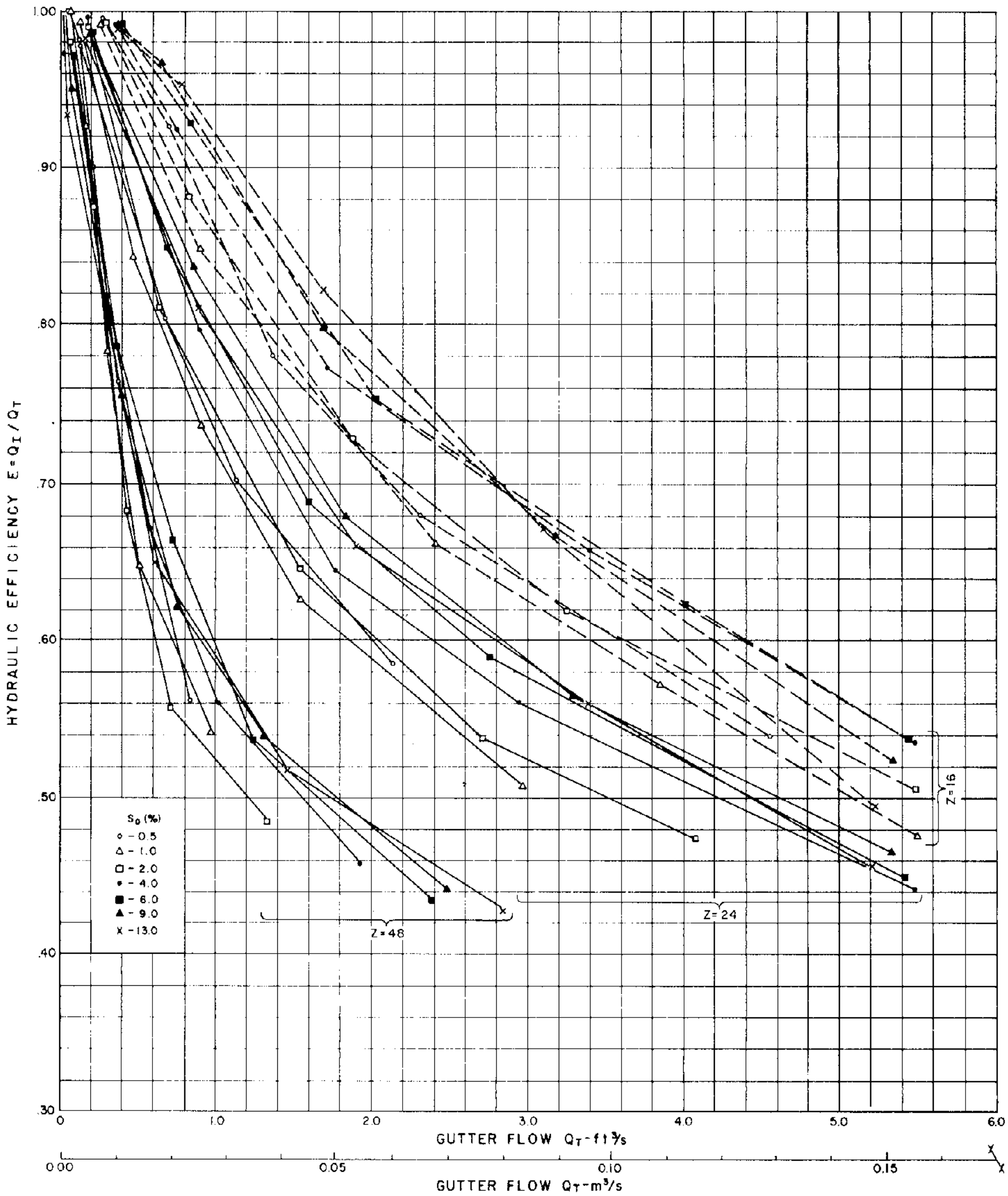


Figure 4-4. - Hydraulic efficiency vs. gutter flow, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) CV - 3-1/4 - 4-1/4 grate.

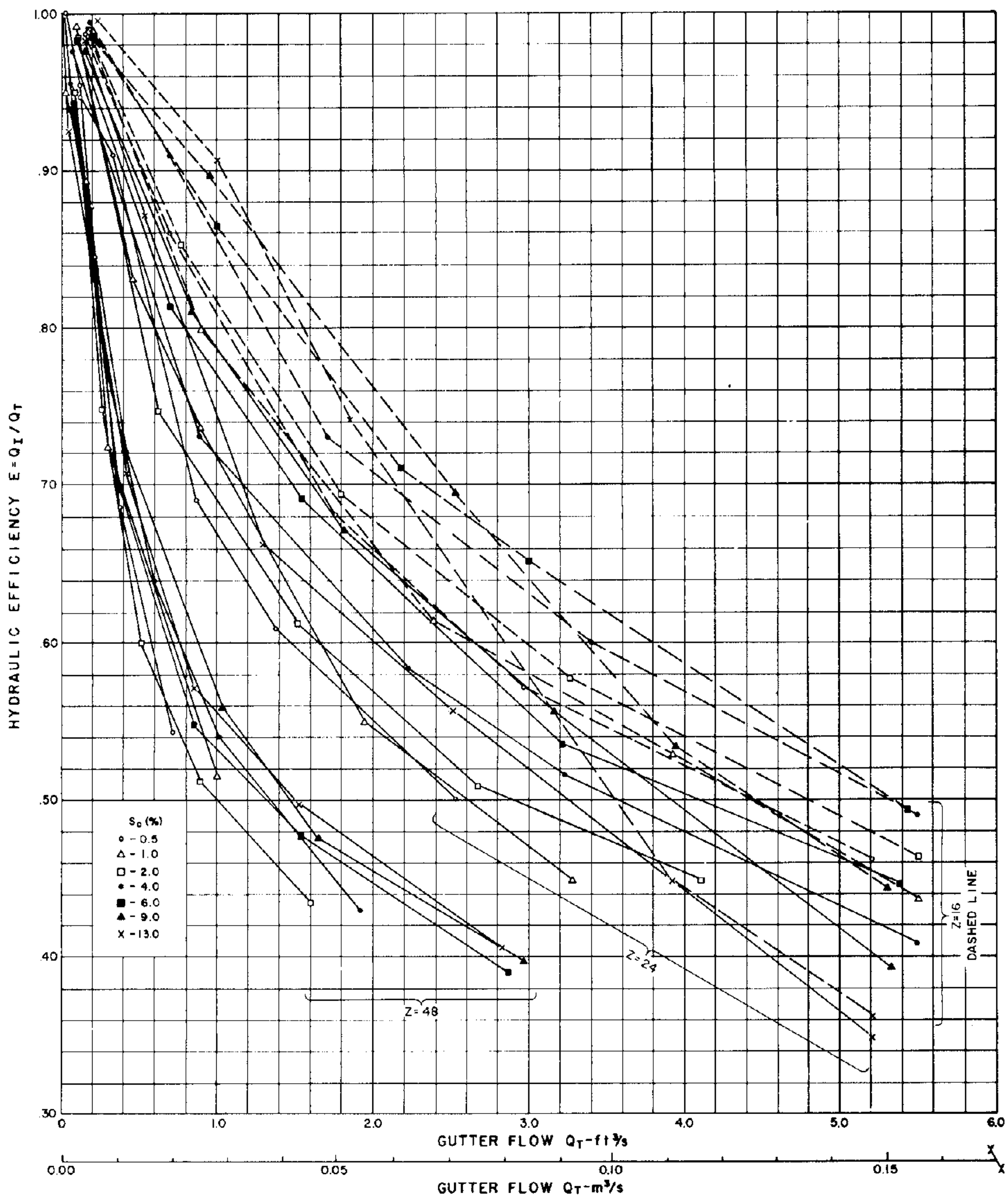


Figure 4-5. - Hydraulic efficiency vs. gutter flow,
1.25 ft by 2.0 ft (0.38 m by 0.61 m)
CV - 3-1/4 - 4-1/4 grate.

produce a flow layer at the surface which reduces the grate's efficiency. The results of this flow layer are particularly evident for the 1.25 ft by 2 ft (0.38 m by 0.61 m) grate in figure 4-5. At the $1/Z = 1/16$ cross slope condition and for a constant gutter flow, the hydraulic efficiency, E, increases with an increase in longitudinal slope, S_0, to a particular slope, $S_0 = 6$ percent, and then decreases at higher longitudinal slopes. The sequence of photographs in figure 4-6 shows the development of this flow layer for the 1.25 ft by 2 ft (0.38 m by 0.61 m) grate at $1/Z = 1/16$ for longitudinal slope conditions of $S_0 = 4$, 6, 9, and 13 percent.

By studying figures 4-2 through 4-5 and the grate inlet capacity curves for the CV - 3-1/4 - 4-1/4, the maximum efficiency longitudinal slopes can be identified for the four grate sizes studied. These are presented in table 4-1.

The maximum efficiency slopes identify the approximate longitudinal slope and cross slope. When this longitudinal slope is exceeded the hydraulic efficiency decreases rapidly as a result of splashing over the transverse bars.

Figures 4-7 through 4-10 show the relationship between measured width of spread, T', and hydraulic efficiency, E, for the four grate sizes tested. For the same width of spread, T', hydraulic efficiencies increase as the longitudinal slope is decreased.

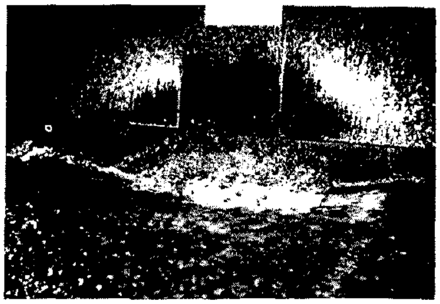
Figures 4-11 through 4-22 present the 12 grate inlet capacity curves for the four CV - 3-1/4 - 4-1/4 grate sizes and three cross slope conditions tested. These curves further identify the maximum efficiency longitudinal slopes by the change in direction of the hydraulic efficiency curves.

Summary

The curved vane grates have excellent hydraulic efficiency and debris handling characteristics as discussed in this chapter and chapter 10 of volume 1.

Figures 4-23 through 4-25 compare the hydraulic efficiencies of the four grate sizes covered in this chapter and the two grate sizes discussed in chapter 10 of volume 1. A width of spread, T', near the maximum tested, was selected for each of the three cross slope conditions. To maintain the width of spread constant, the gutter flow, Q_T, increases as the longitudinal slope is increased. As one would expect, there is a decrease in hydraulic efficiency as the longitudinal slope is increased and the width of spread held constant.

As with the P - 1-1/8 and P - 1-7/8 - 4 grates, there are several conclusions which can be stated about the CV - 3-1/4 - 4-1/4 grate based on a review of figures 4-23 through 4-25.

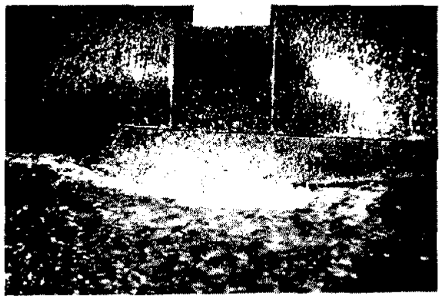


a. $S_0 = 4\%$

$Q_T = 5.50\ ft^3/s\ (0.156\ m^3/s)$

$T' = 5.5\ ft\ (1.68\ m)$

$E = 49.1\%$



b. $S_0 = 6\%$

$Q_T = 5.50\ ft^3/s\ (0.156\ m^3/s)$

$T' = 5.2\ ft\ (1.58\ m)$

$E = 49.4\%$

c. $S_0 = 9\%$

$Q_T = 5.31\ ft^3/s\ (0.150\ m^3/s)$

$T' = 4.9\ ft\ (1.49\ m)$

$E = 44.4\%$

d. $S_0 = 13\%$

$Q_T = 5.21\ ft^3/s\ (0.148\ m^3/s)$

$T' = 4.4\ ft\ (1.34\ m)$

$E = 36\%$

Figure 4-6. - Development of the flow layer on the 1.25 ft by 2.0 ft (0.38 m by 0.61 m) CV - 3-1/4 - 4-1/4 grate, Z = 16. Photo 1765-440

Table 4-1. - *Maximum efficiency longitudinal slopes for CV - 3-1/4 - 4-1/4 grates*

	3.0 by 4.0 ft (0.91 by 1.22 m)	3.0 by 2.0 ft (0.91 by 0.61 m)	1.25 by 2.67 ft (0.38 by 0.81 m)	1.25 by 2.0 ft (0.38 by 0.61 m)
1/Z = 1/16	≥13%	5-9%	6-13%	6%
1/Z = 1/24	≥13%	≥13%	≥13%	6%
1/Z = 1/48	≥13%	≥13%	≥13%	≥13%

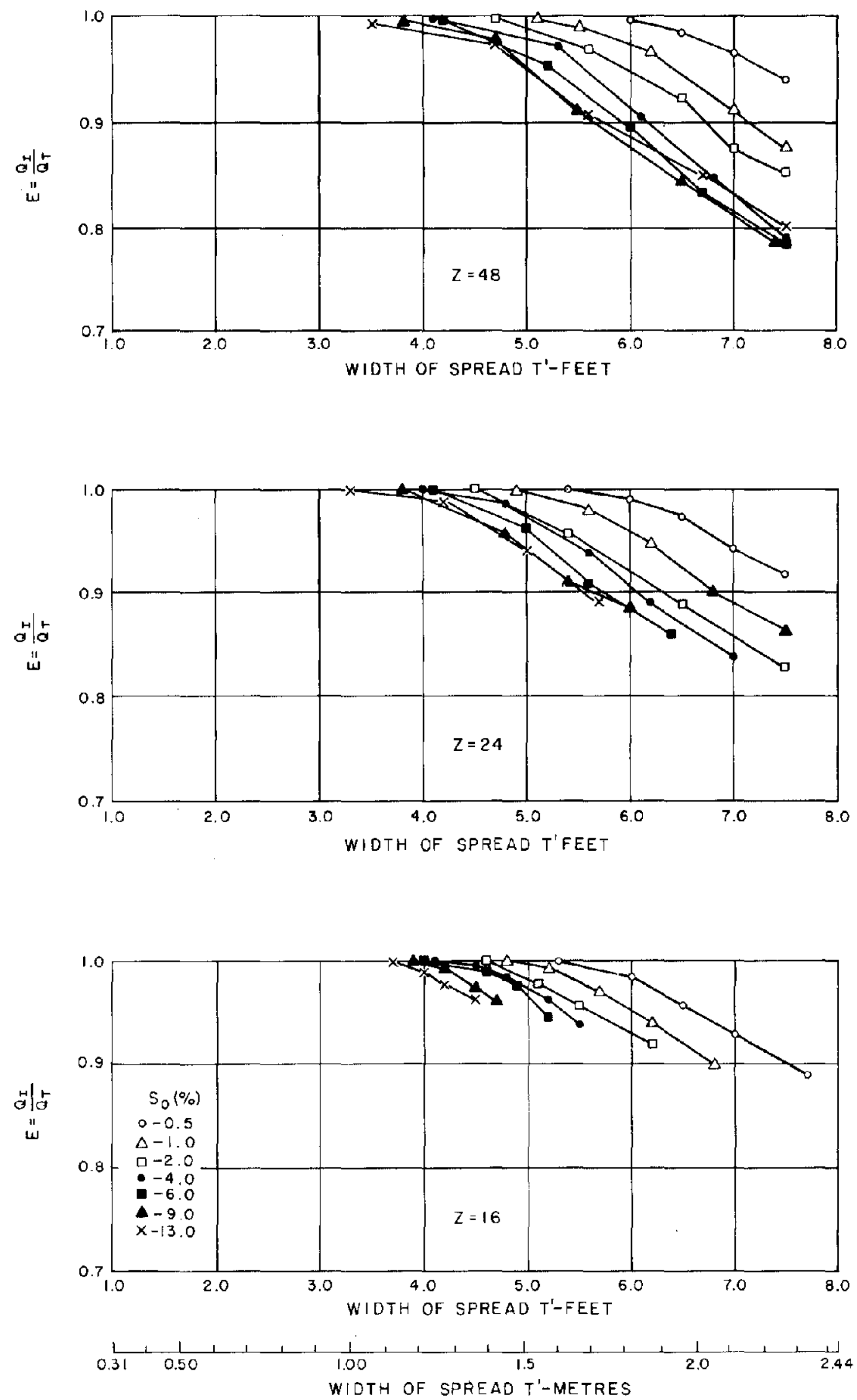


Figure 4-7. - Hydraulic efficiency vs. width of spread 3.0 ft by 4.0 ft (0.91 m by 1.22 m) CV - 3-1/4 - 4-1/4 grate.

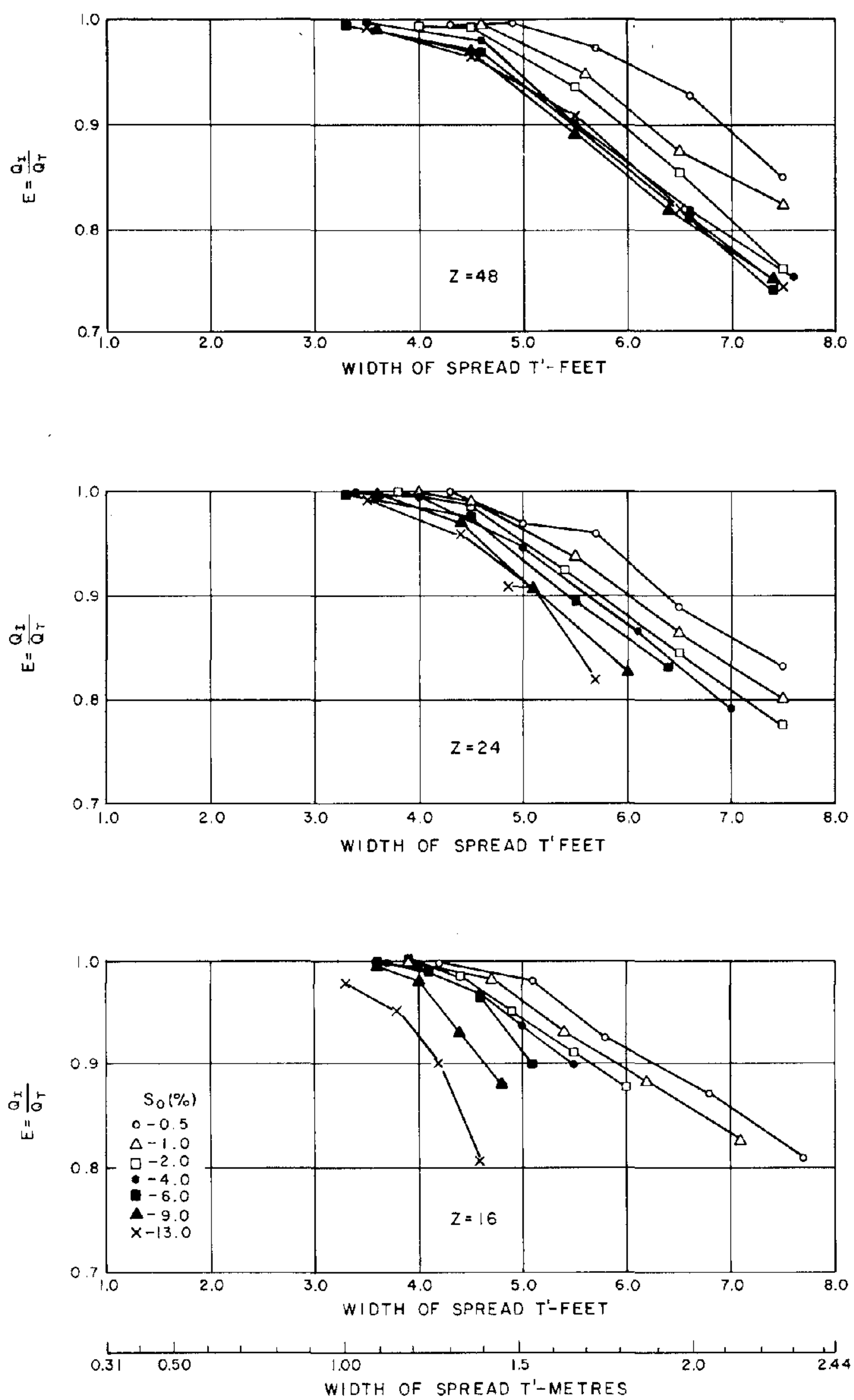


Figure 4-8. - Hydraulic efficiency vs. width of spread
3.0 ft by 2.0 ft (0.91 m by 0.61 m)
CV - 3-1/4 - 4-1/4 grate.

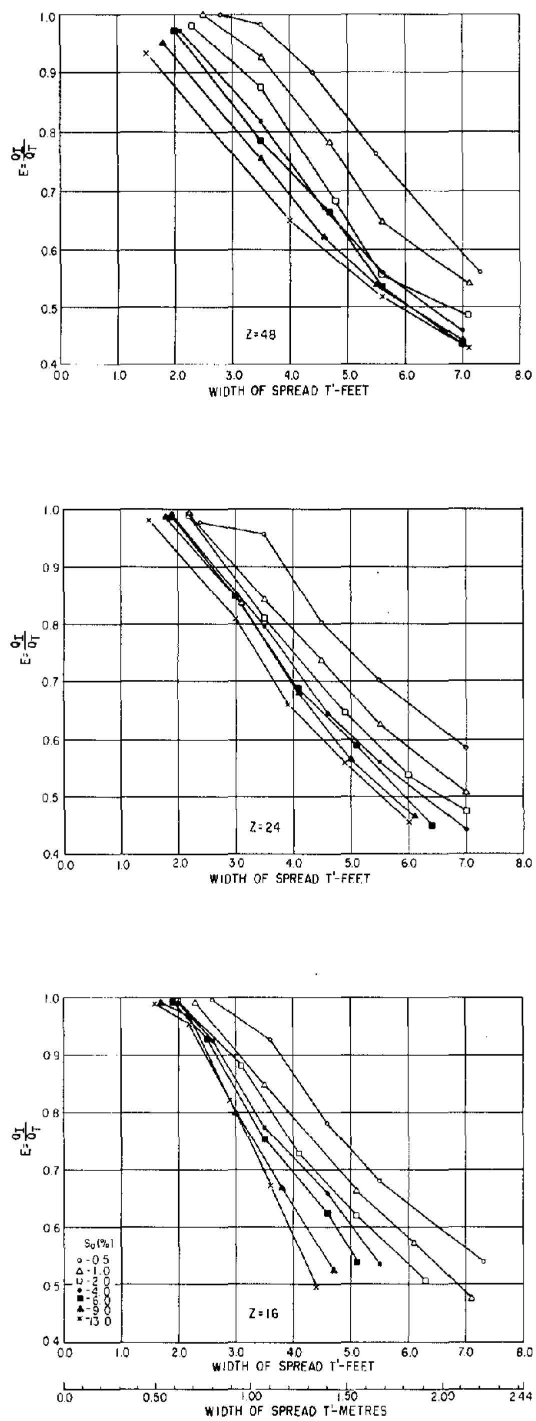


Figure 4-9. - Hydraulic efficiency vs. width of spread 1.25 ft by 2.67 ft (0.38 m by 0.81 m) CV - 3-1/4 - 4-1/4 grate.

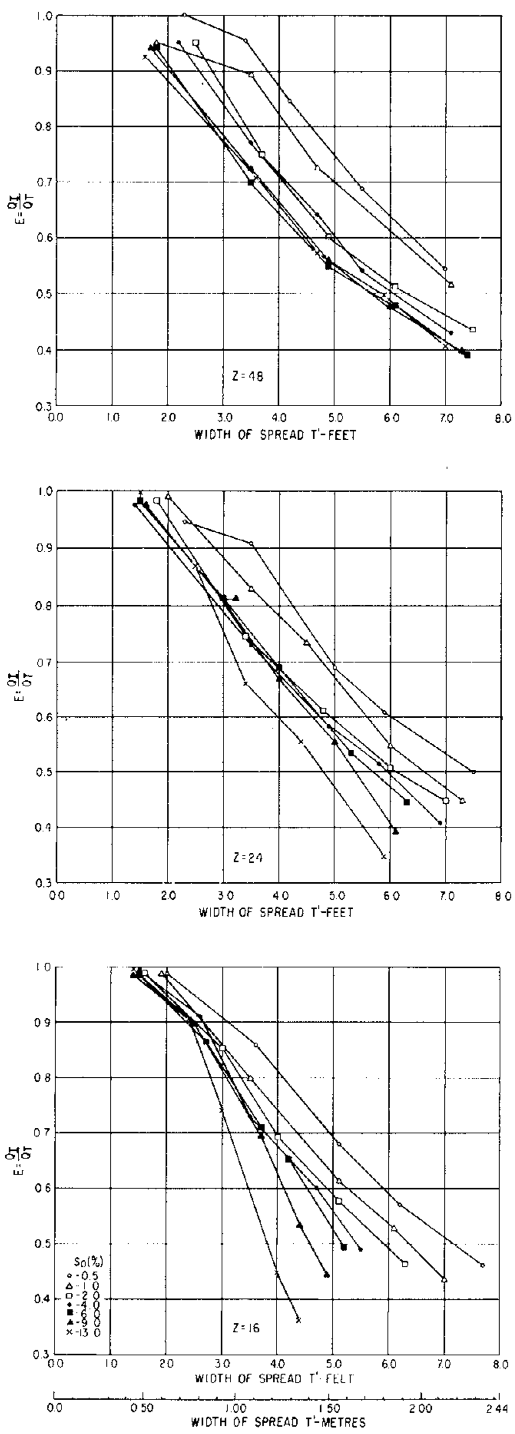


Figure 4-10. - Hydraulic efficiency vs. width of spread 1.25 ft by 2.0 ft (0.38 m by 0.61 m) CV - 3-1/4 - 4-1/4 grate.

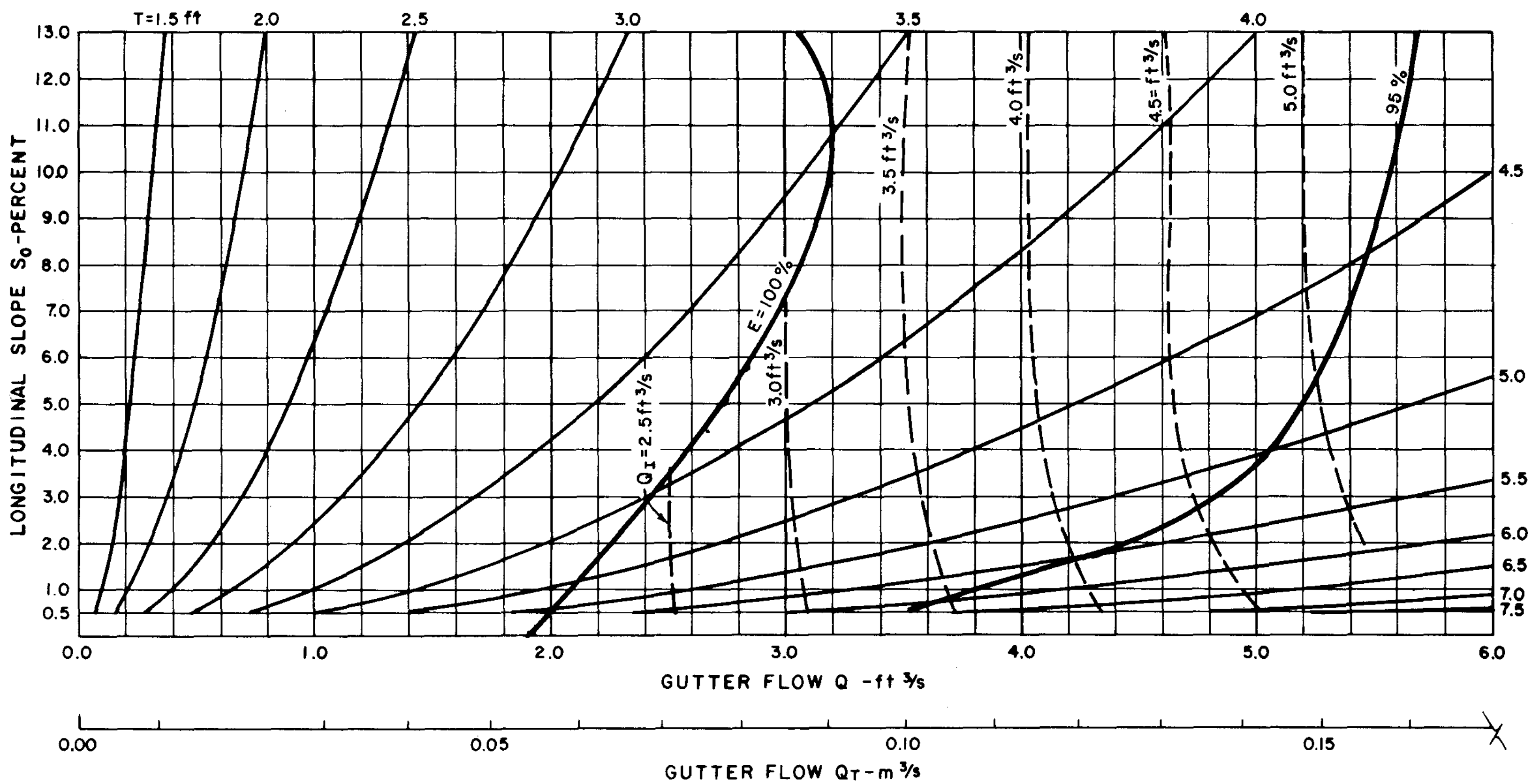


Figure 4-11. - Grate inlet capacity curves, 3.0 ft by 4.0 ft (0.91 m by 1.22 m)
CV - 3-1/4 - 4-1/4 grate, Z = 16.

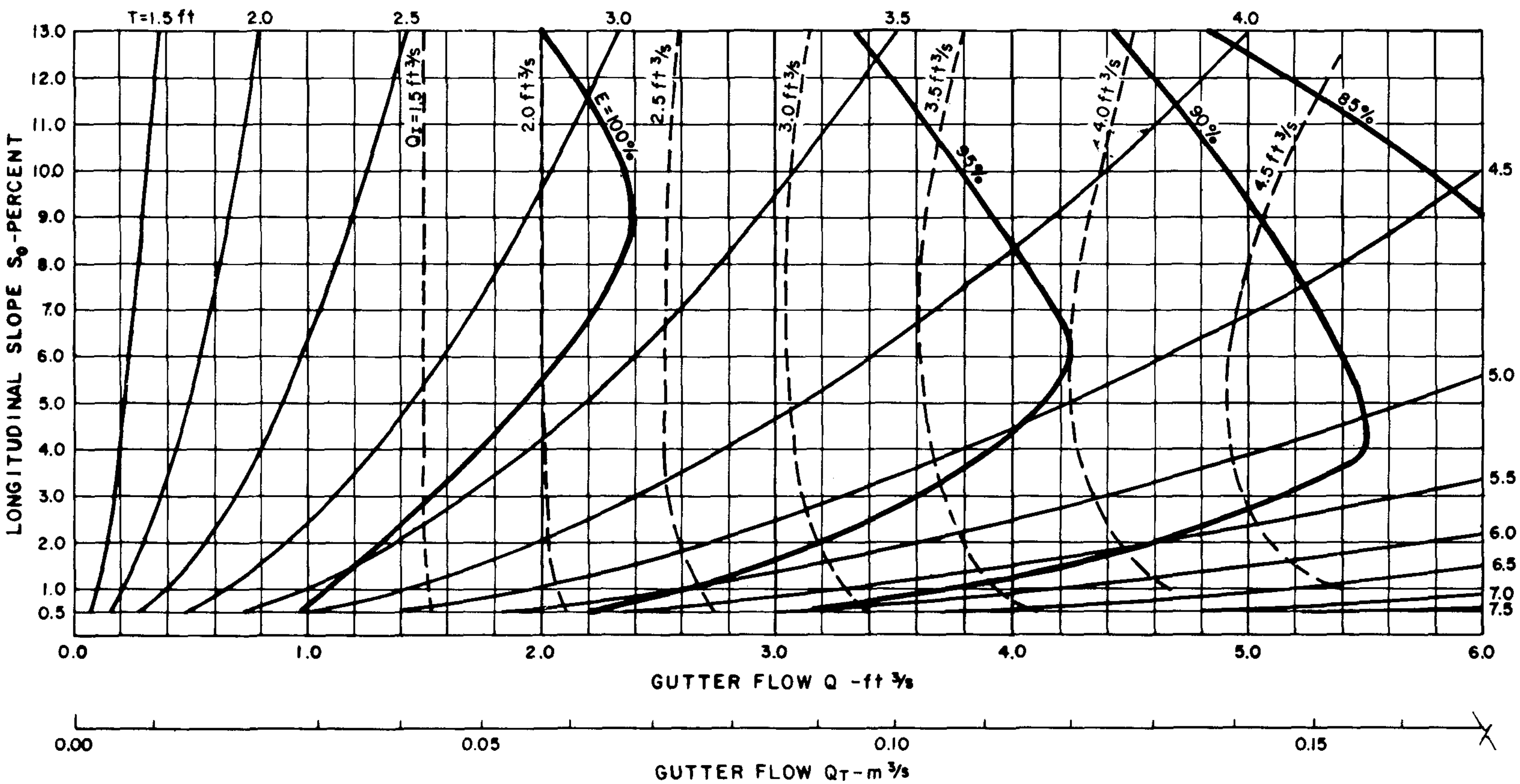


Figure 4-12. - Grate inlet capacity curves, 3.0 ft by 2.0 ft (0.91 m by 0.61 m) CV - 3-1/4 - 4-1/4 grate, Z = 16.

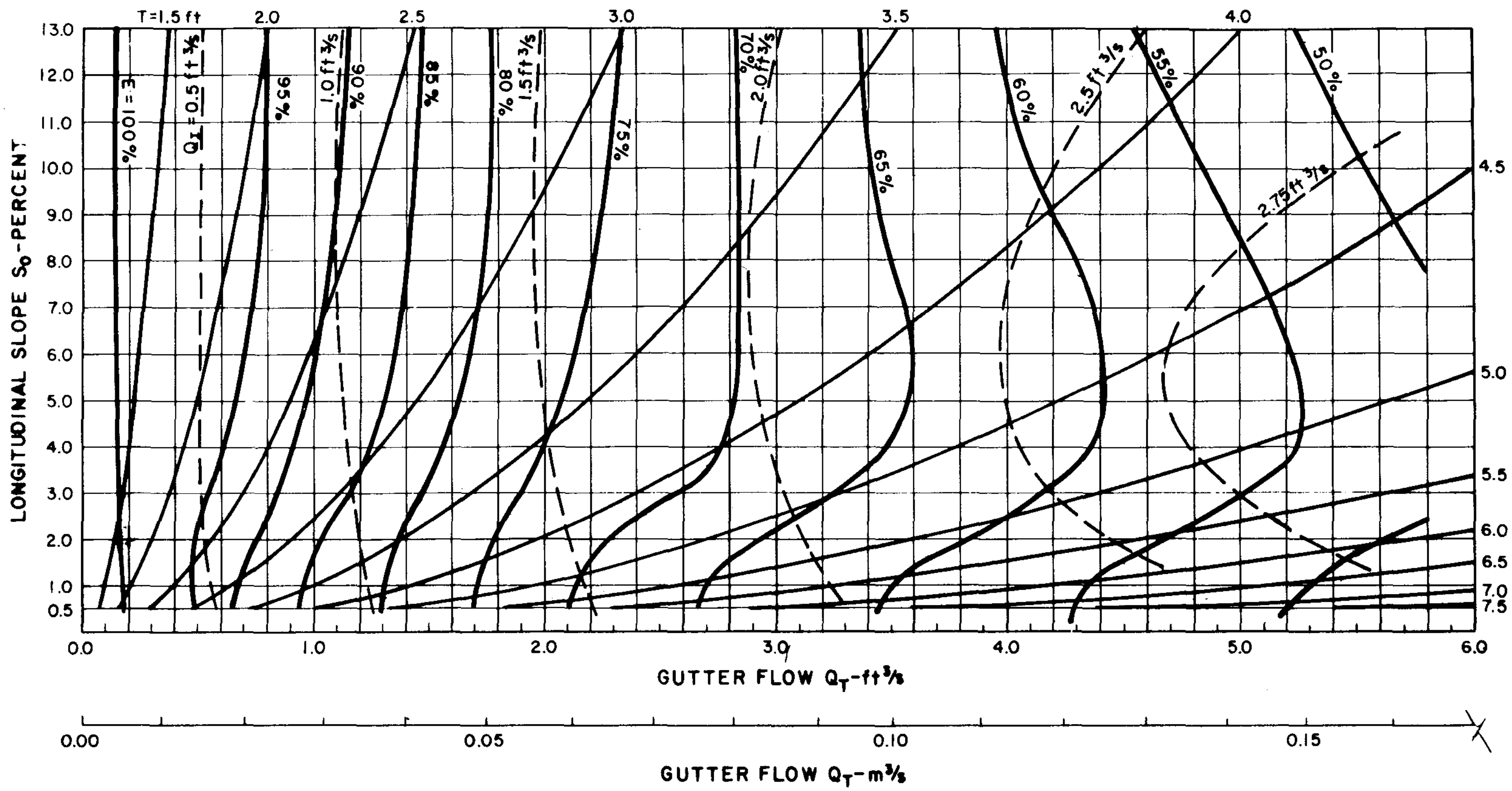


Figure 4-13. - Grate inlet capacity curves, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) CV - 3-1/4 - 4-1/4 grate, Z = 16.

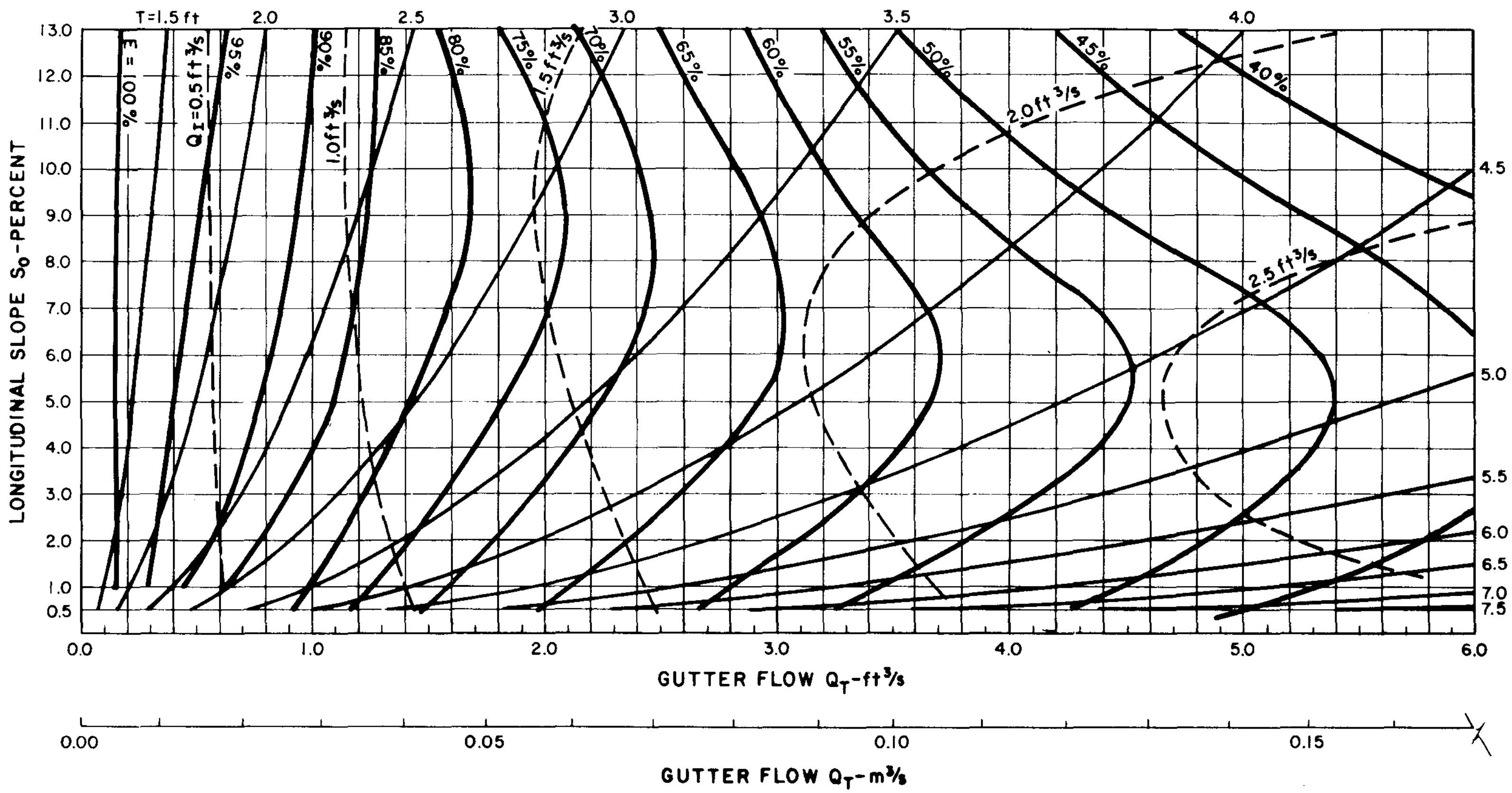


Figure 4-14. - Grate inlet capacity curves, 1.25 ft by 2.0 ft (0.38 m by 0.61 m) CV - 3-1/4 - 4-1/4 grate, Z = 16.

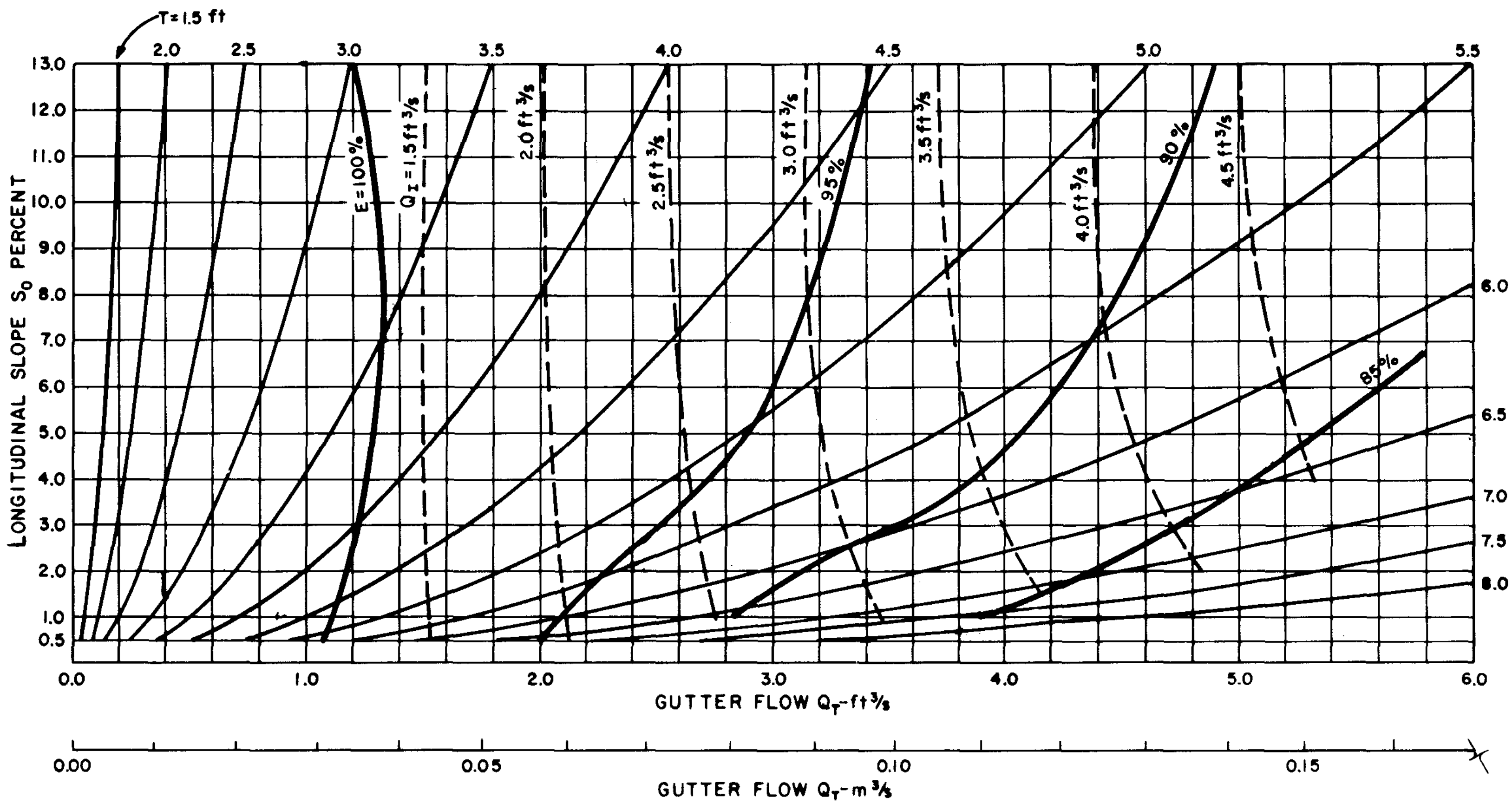


Figure 4-15. - Grate inlet capacity curves, 3.0 ft by 4.0 ft (0.91 m by 1.22 m)
CV - 3-1/4 - 4-1/4 grate, Z = 24.

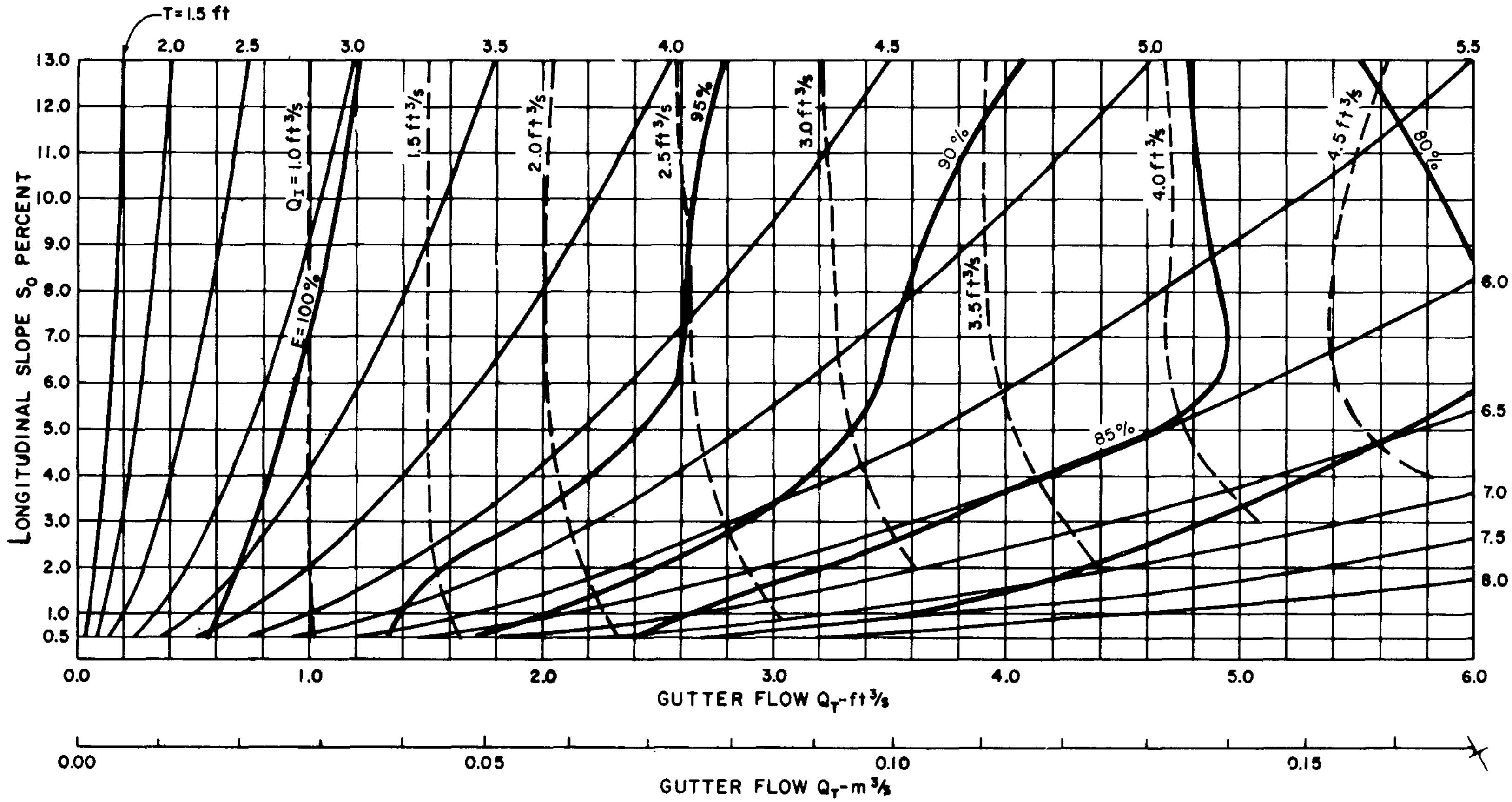


Figure 4-16. - Grate inlet capacity curves, 3.0 ft by 2.0 ft (0.91 m by 0.61 m)
CV - 3-1/4 - 4-1/4 grate, Z = 24.

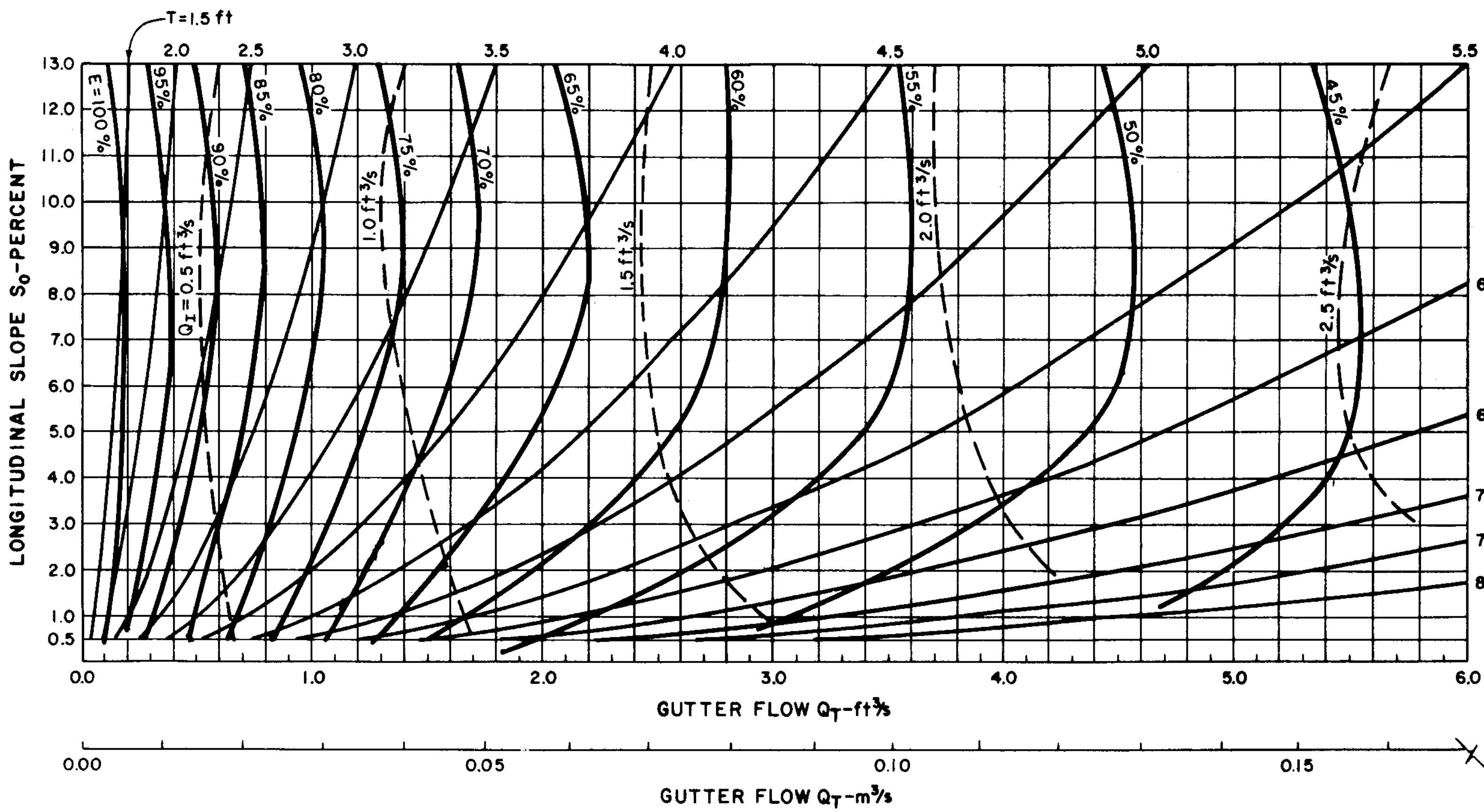


Figure 4-17. - Grate inlet capacity curves, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) CV - 3-1/4 - 4-1/4 grate, Z = 24.

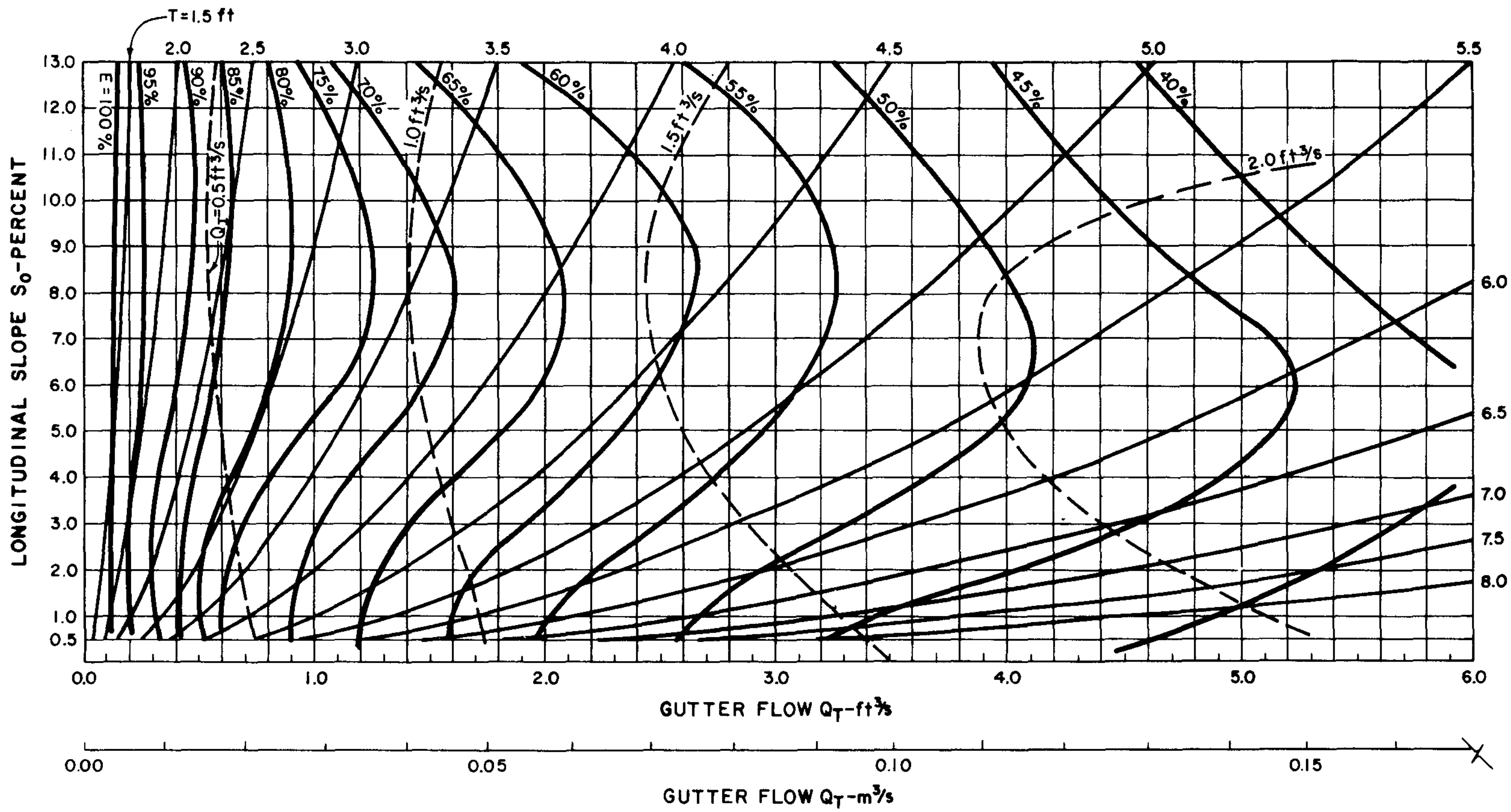


Figure 4-18. - Grate inlet capacity curves, 1.25 ft by 2.0 ft (0.38 m by 0.61 m)
CV - 3-1/4 - 4-1/4 grate, Z = 24.

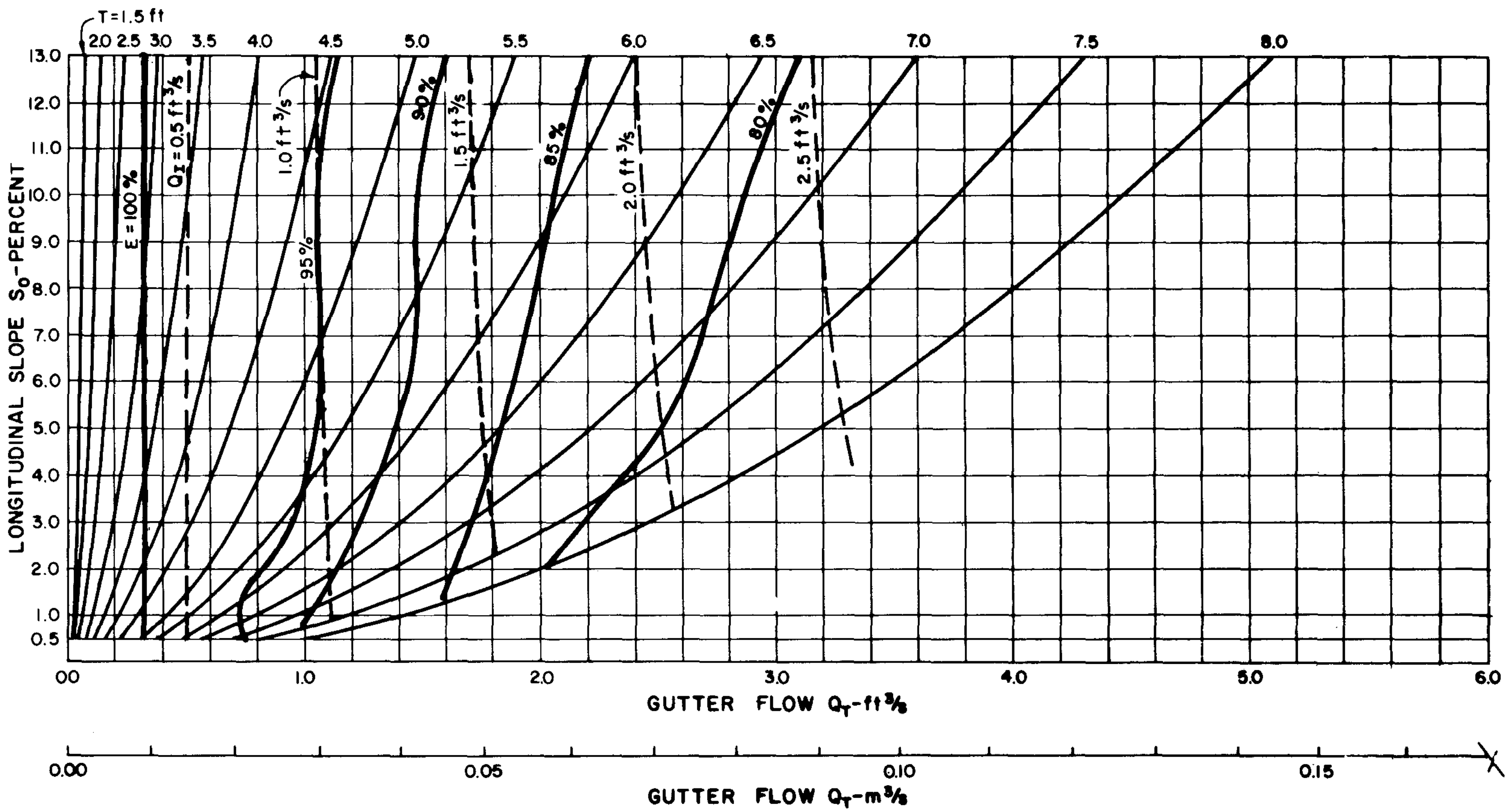


Figure 4-19. - Grate inlet capacity curves, 3.0 ft by 4.0 ft (0.91 m by 1.22 m)
CV - 3-1/4 - 4-1/4 grate, Z = 48.

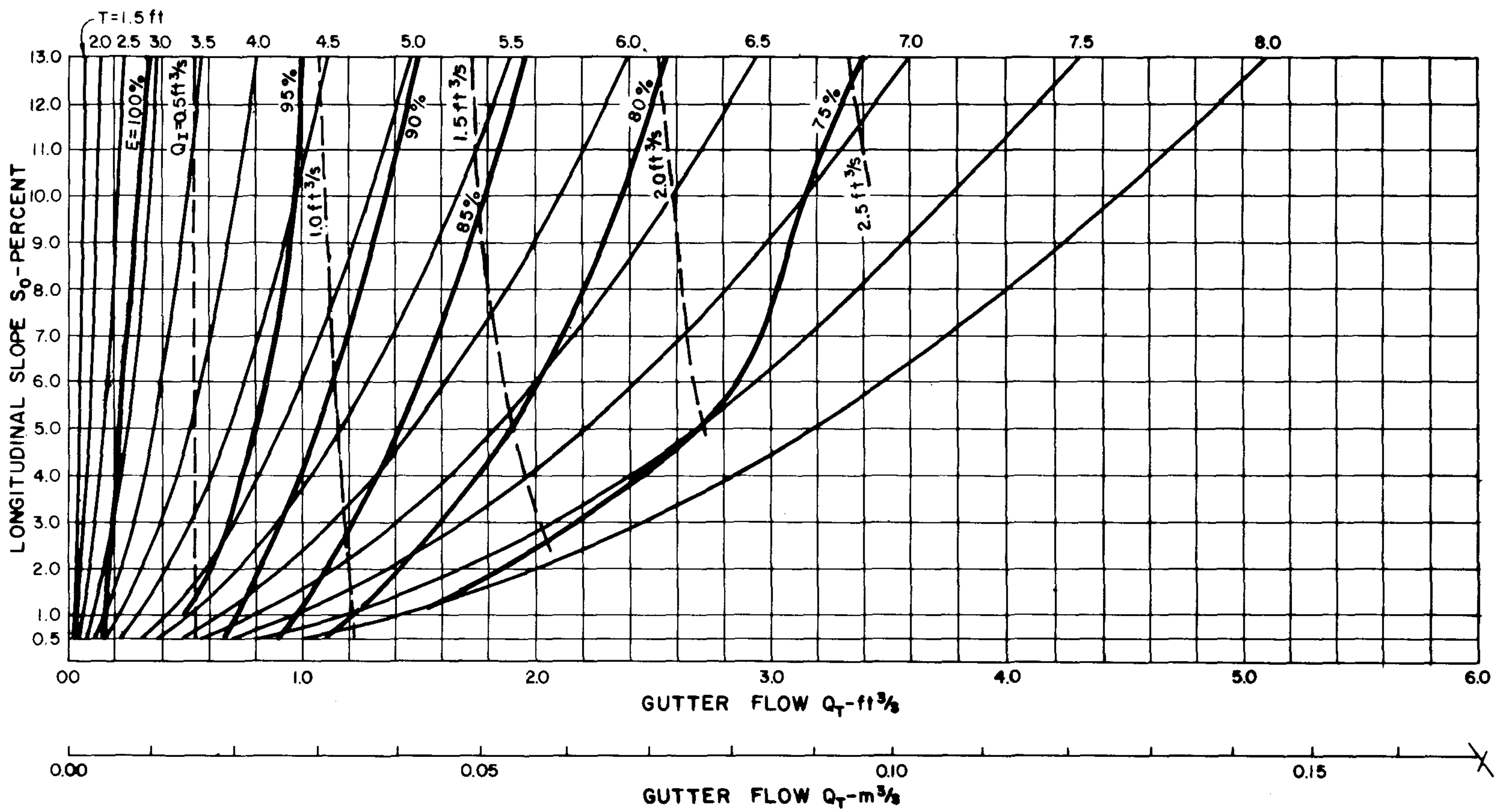


Figure 4-20. - Grate inlet capacity curves, 3.0 ft by 2.0 ft (0.91 m by 0.61 m) CV - 3-1/4 - 4-1/4 grate, Z = 48.

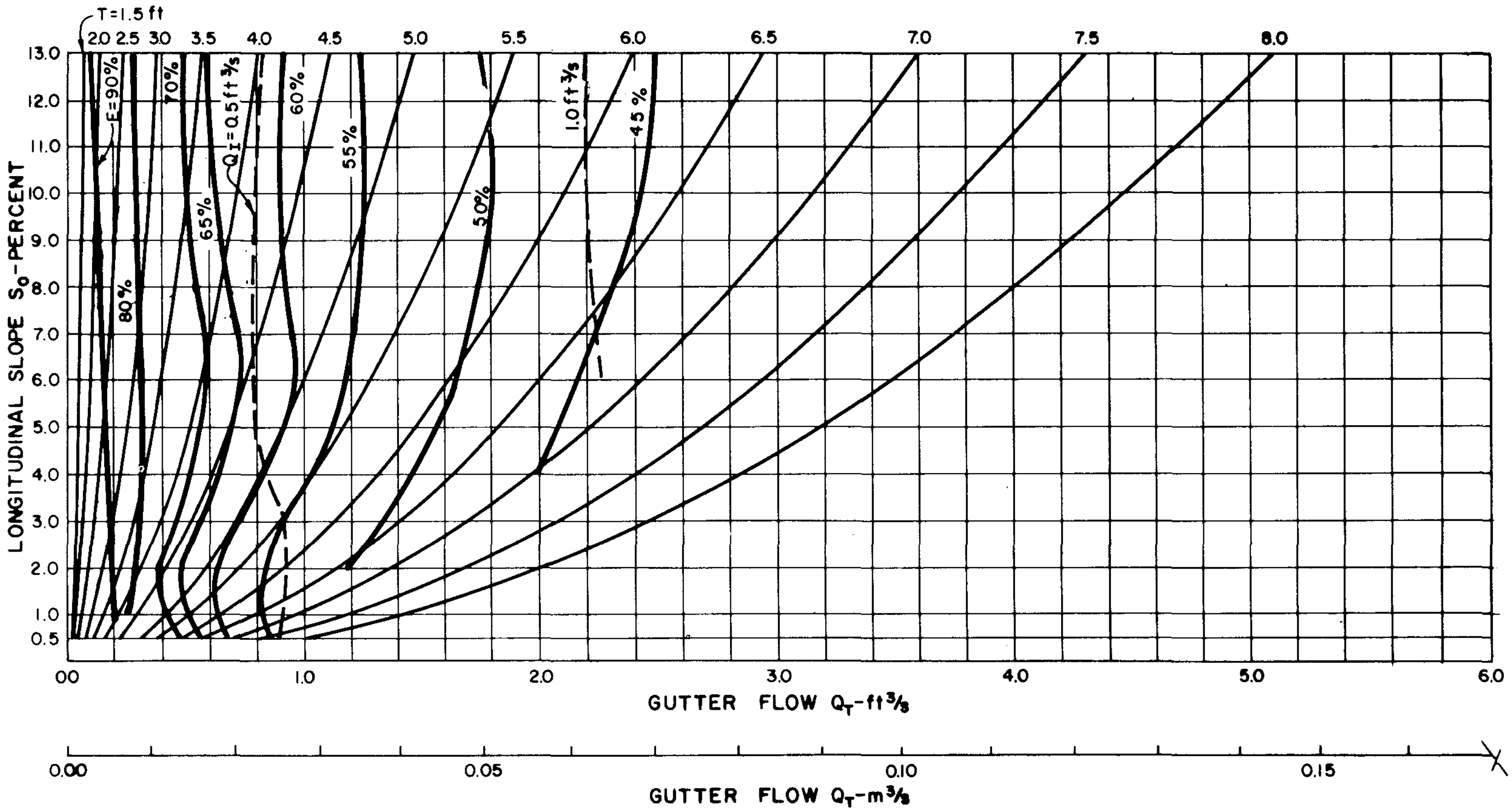


Figure 4-21. - Grate inlet capacity curves, 1.25 ft by 2.67 ft (0.38 m by 0.81 m)
CV - 3-1/4 - 4-1/4 grate, Z = 48.

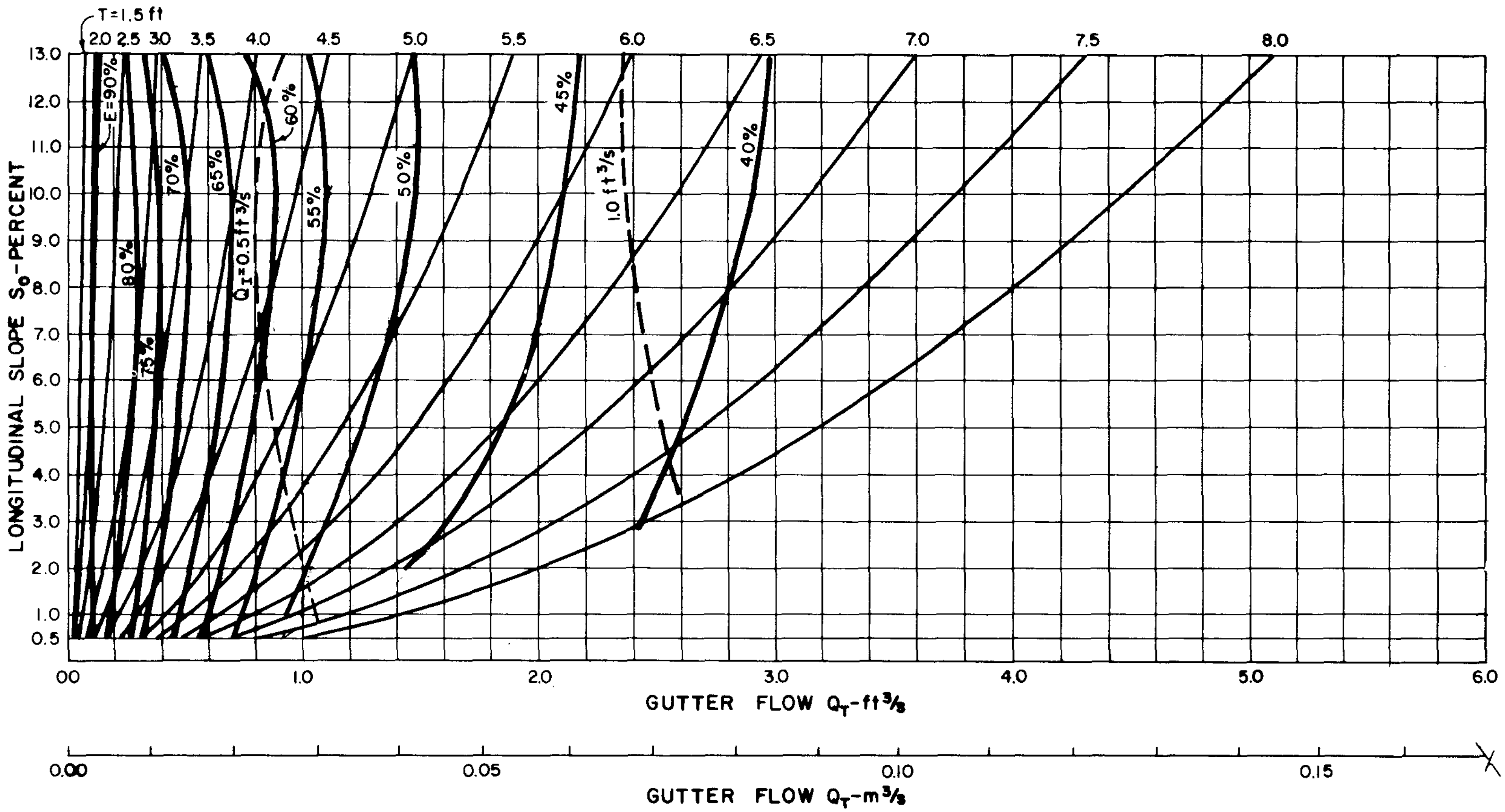


Figure 4-22. - Grate inlet capacity curves, 1.25 ft by 2.0 ft (0.38 m by 0.61 m) CV - 3-1/4 - 4-1/4 grate, Z = 48.

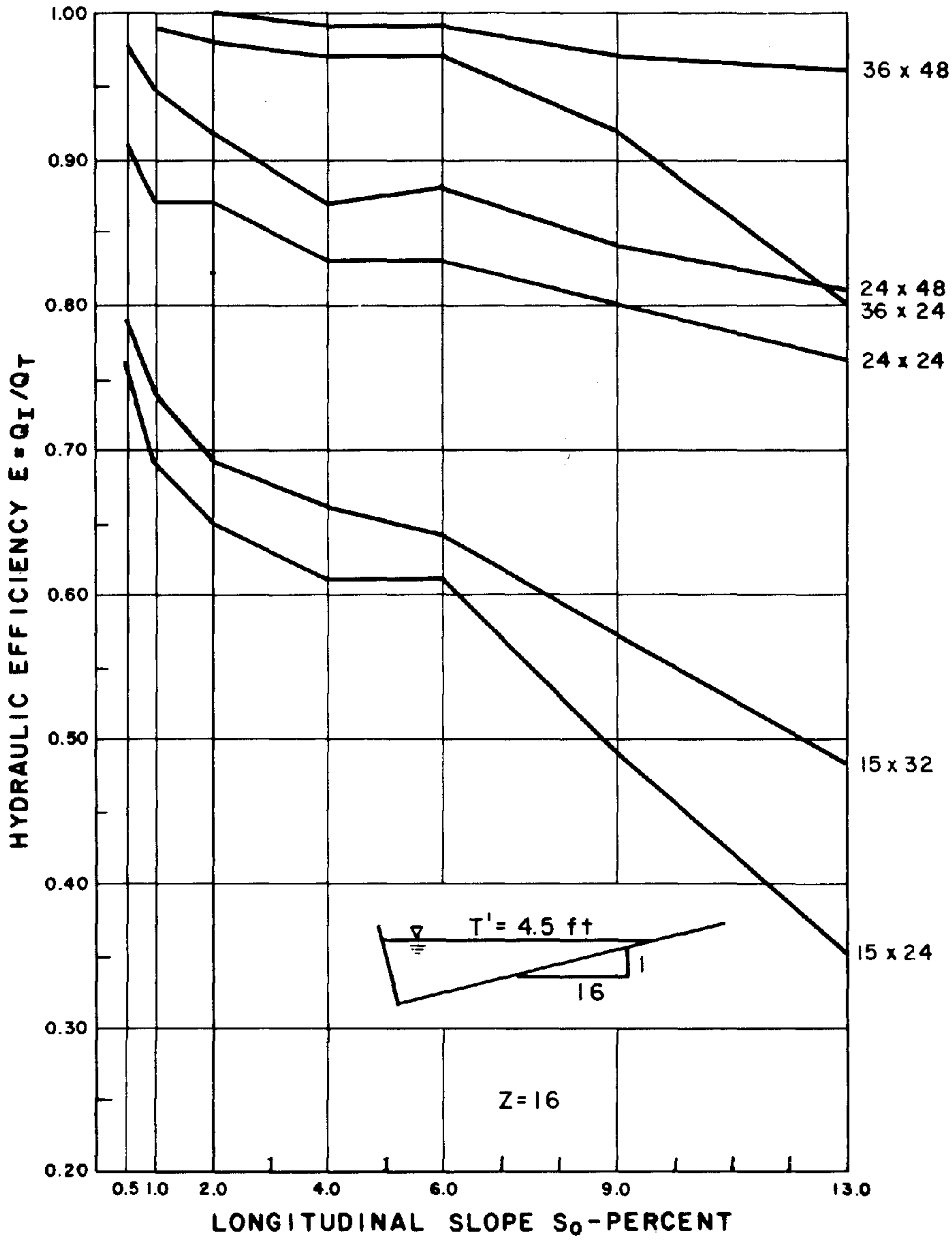


Figure 4-23. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, CV - 3-1/4 - 4-1/4 grate, T' = 4.5 ft (1.37 m), Z = 16.

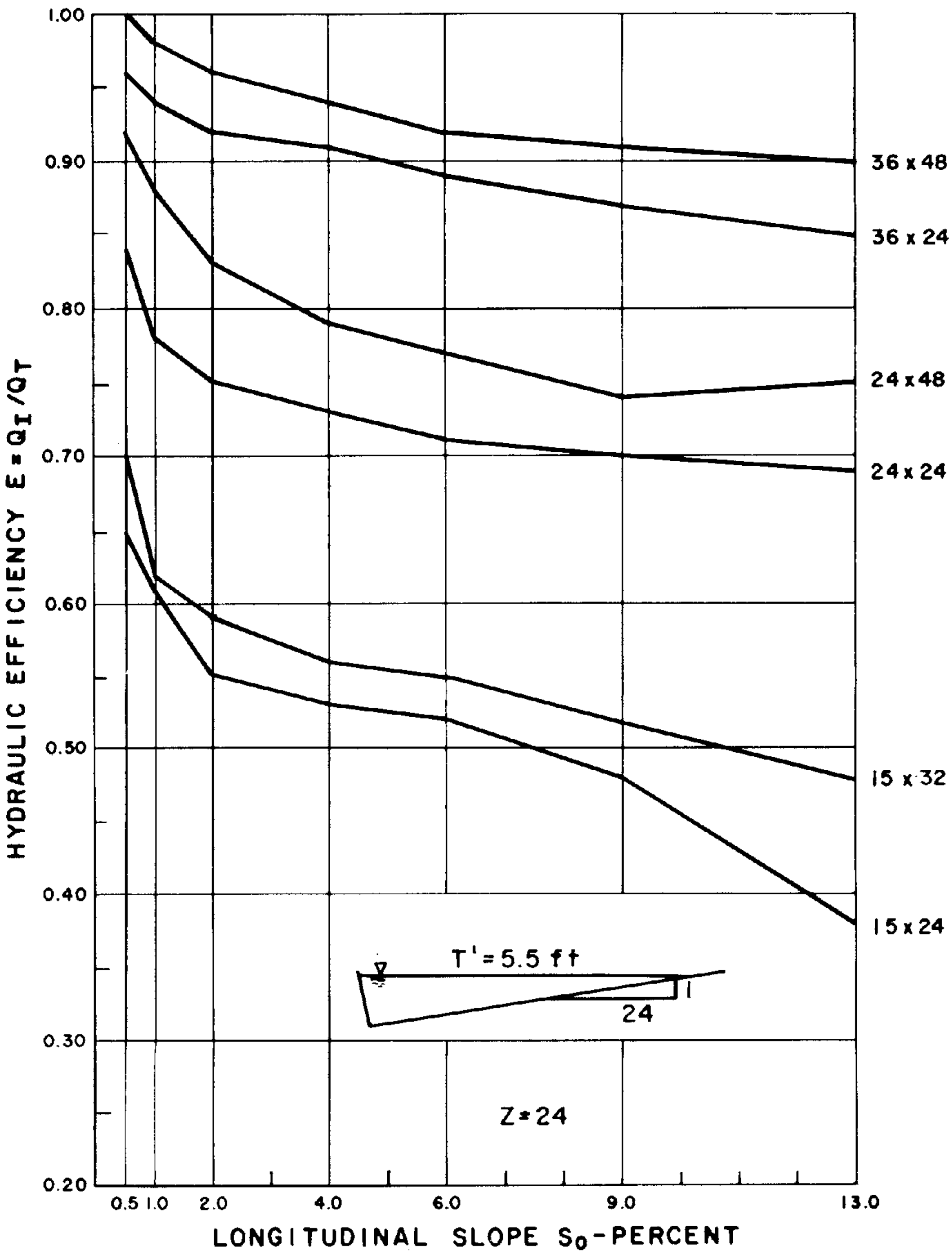


Figure 4-24. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, CV - 3-1/4 - 4-1/4 grate, T' = 5.5 ft (1.68 m), Z = 24.

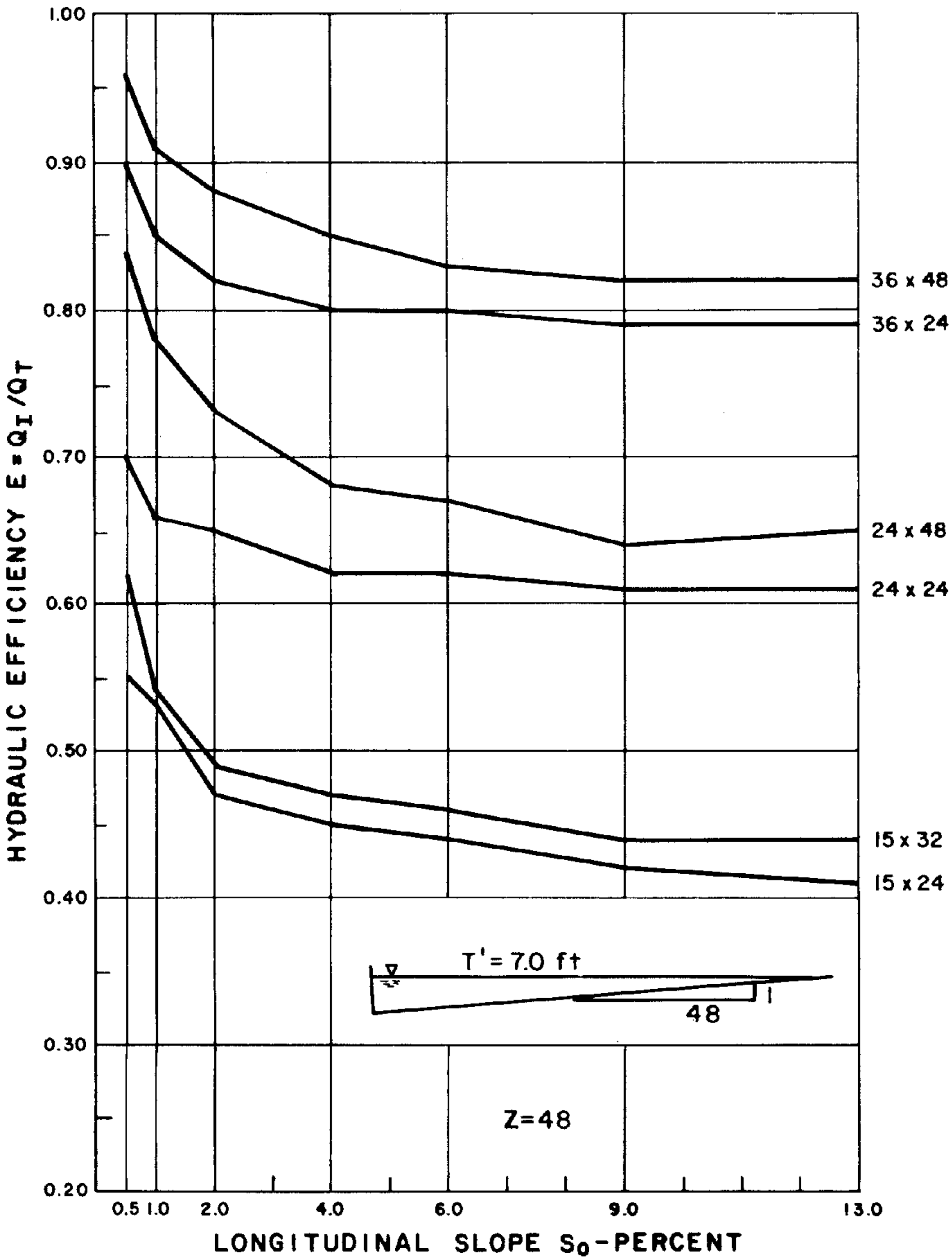


Figure 4-25. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, CV - 3-1/4 - 4-1/4 grate, T' = 7.0 ft (2.13 m), Z = 48.

1. The grate width is an important variable with respect to hydraulic efficiency. Increases in hydraulic efficiency are greater with an incremental increase in grate width as compared to the same increase in grate length. With the exception of the 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grate at S_0 = 13 percent in figure 4-23, the wider grates are more efficient, irrespective of grate length.

2. For high-energy gutter flow, the hydraulic efficiency of the CV - 3-1/4 - 4-1/4 grate decreases rapidly for inadequate grate sizes. This is evident with the 1.25 ft by 2.0 ft, 1.25 ft by 2.67 ft, and 3.0 ft by 2.0 ft (0.38 m by 0.61 m, 0.38 m by 0.81 m, and 0.91 m by 0.61 m) grates in figure 4-23 and the 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grate in figure 4-24.

CHAPTER 5

DISCUSSION OF RESULTS AND CONCLUSIONS

Discussion of Results

As discussed in volume 1, the flow into and around each of the three grate styles is similar in many respects to the flow conditions near an open hole. For a constant gutter flow, all the grates show some increase in hydraulic efficiency if the cross slope is held constant and the longitudinal slope is increased. At the steeper longitudinal slopes a greater percentage of the gutter flow passes over the grate inlet. If no flow splashes over the grate, intercepted flow is greater and hence hydraulic efficiency is higher. This pattern of increased efficiency occurs for all three grates tested until a slope is reached where the increased velocity causes some of the flow to pass completely over the grate without being captured. Chapters 2, 3, and 4 contain a table for each grate design which identifies the maximum efficiency longitudinal slope for each of the grate sizes and cross slope conditions tested.

The relationship between hydraulic efficiency, E, and gutter flow, Q_T, for each grate design at a given gutter flow condition are compared in figures 5-1 through 5-28. Figures 5-1 through 5-7 present the data for the 3.0 ft by 4.0 ft (0.91 m by 1.22 m) grates for S_0 = 0.5, 1.0, 2.0, 4.0, 6.0, 9.0, and 13.0 percent. Figures 5-8 through 5-14 present the 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates, figures 5-15 through 5-21 present the 1.25 ft by 2.67 ft (0.38 m by 0.81 m) grates, and figures 5-22 through 5-28 present the 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grates.

For gutter flow conditions where no splash occurs, the curves for the various grate designs are close together. The maximum difference in hydraulic efficiency between the grate designs for any gutter flow, Q_T, is approximately 6.0 percent. If the flow does not pass completely over the grate, differences in hydraulic efficiency can only be attributed to minor differences in the effective size of the grates. If one studies the detailed grate drawings in each chapter it is evident that although the nominal outside dimensions of the grates are the same, the effective openings may vary considerably. In general the fabricated steel grates (P - 1-7/8 - 4 and P - 1-1/8) have a larger effective opening than the cast grate (CV - 3-1/4 - 4-1/4). Therefore the fabricated steel grates have slightly higher hydraulic efficiency characteristics than the cast grate at the low-energy gutter flow conditions.

At high-energy gutter flow conditions the design of the individual grate inlets affect the hydraulic efficiency. In general the P - 1-1/8 fabricated steel grate is more efficient than the other

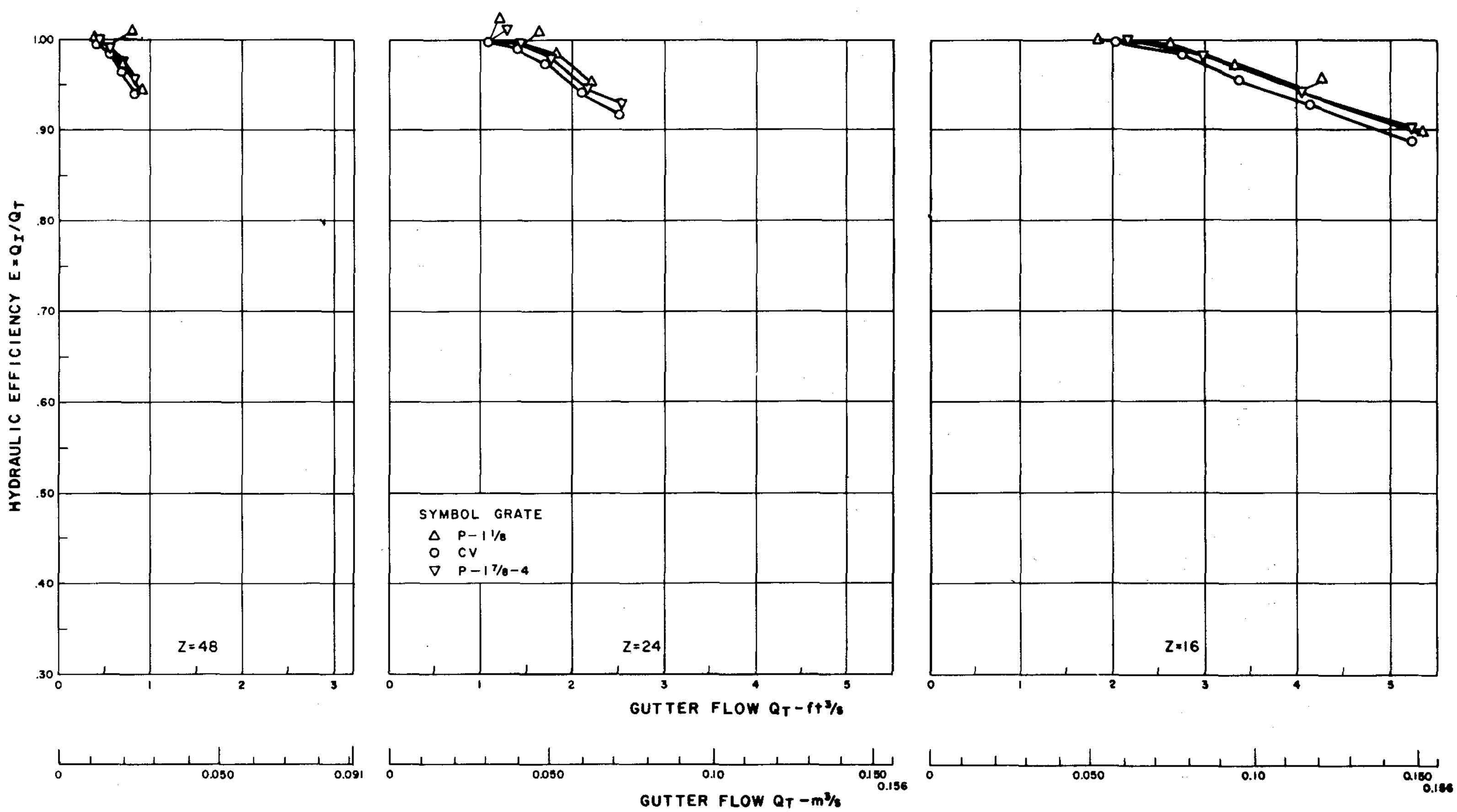


Figure 5-1. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 4.0 ft (0.91 m by 1.22 m) grates, S_0 = 0.5%.

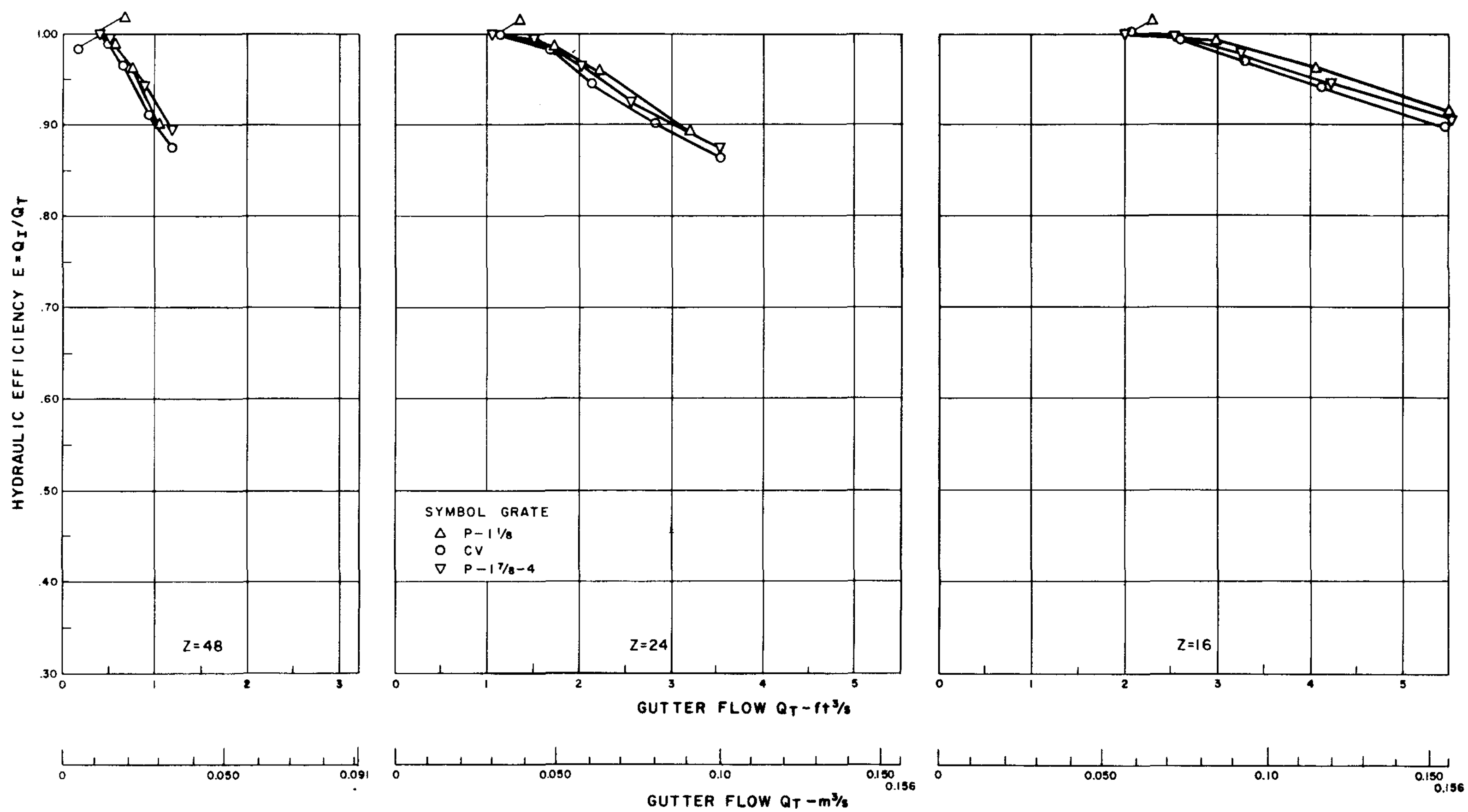


Figure 5-2. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 4.0 ft (0.91 m by 1.22 m) grates, S_0 = 1.0%.

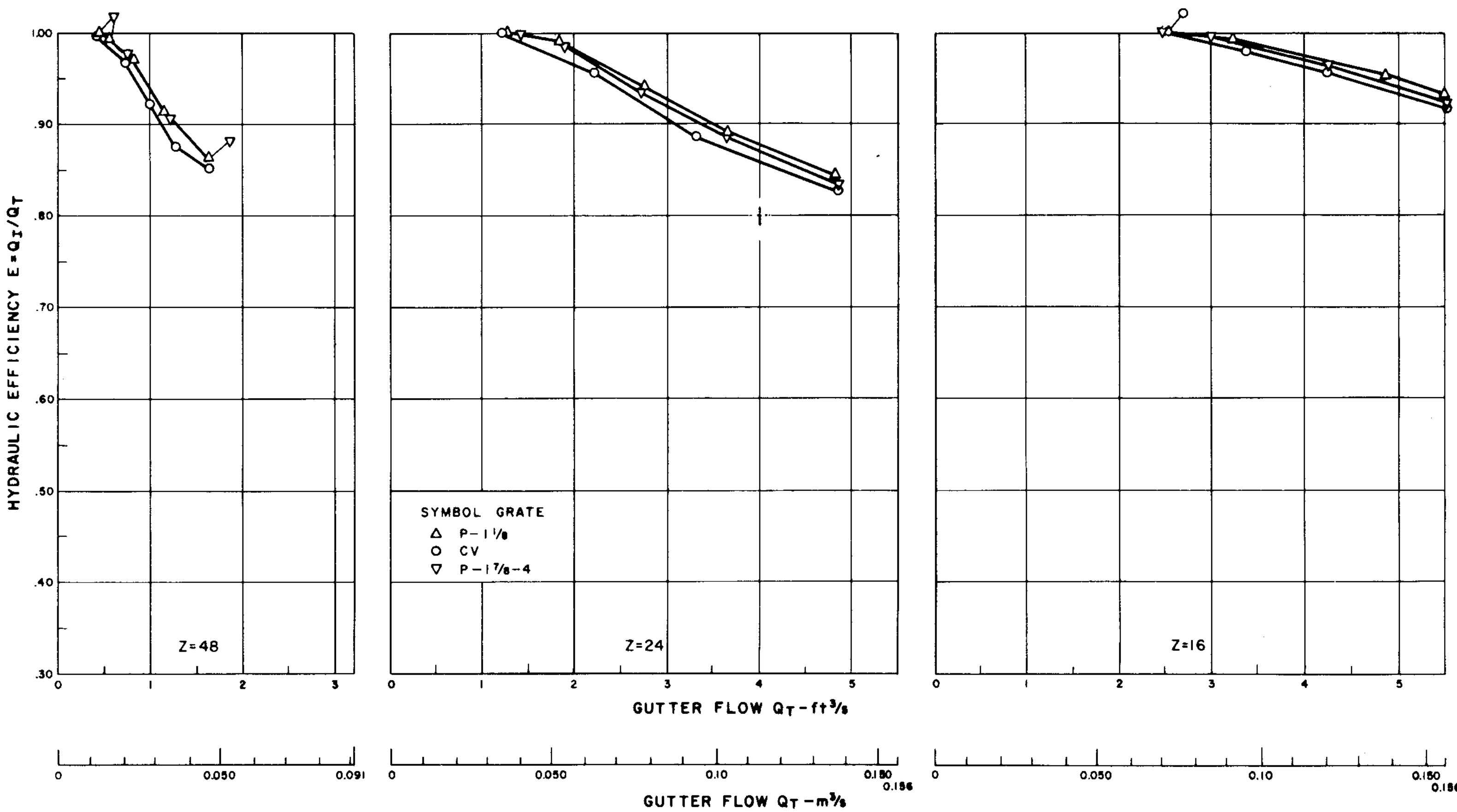


Figure 5-3. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 4.0 ft (0.91 m by 1.22 m) grates, S_0 = 2.0%.

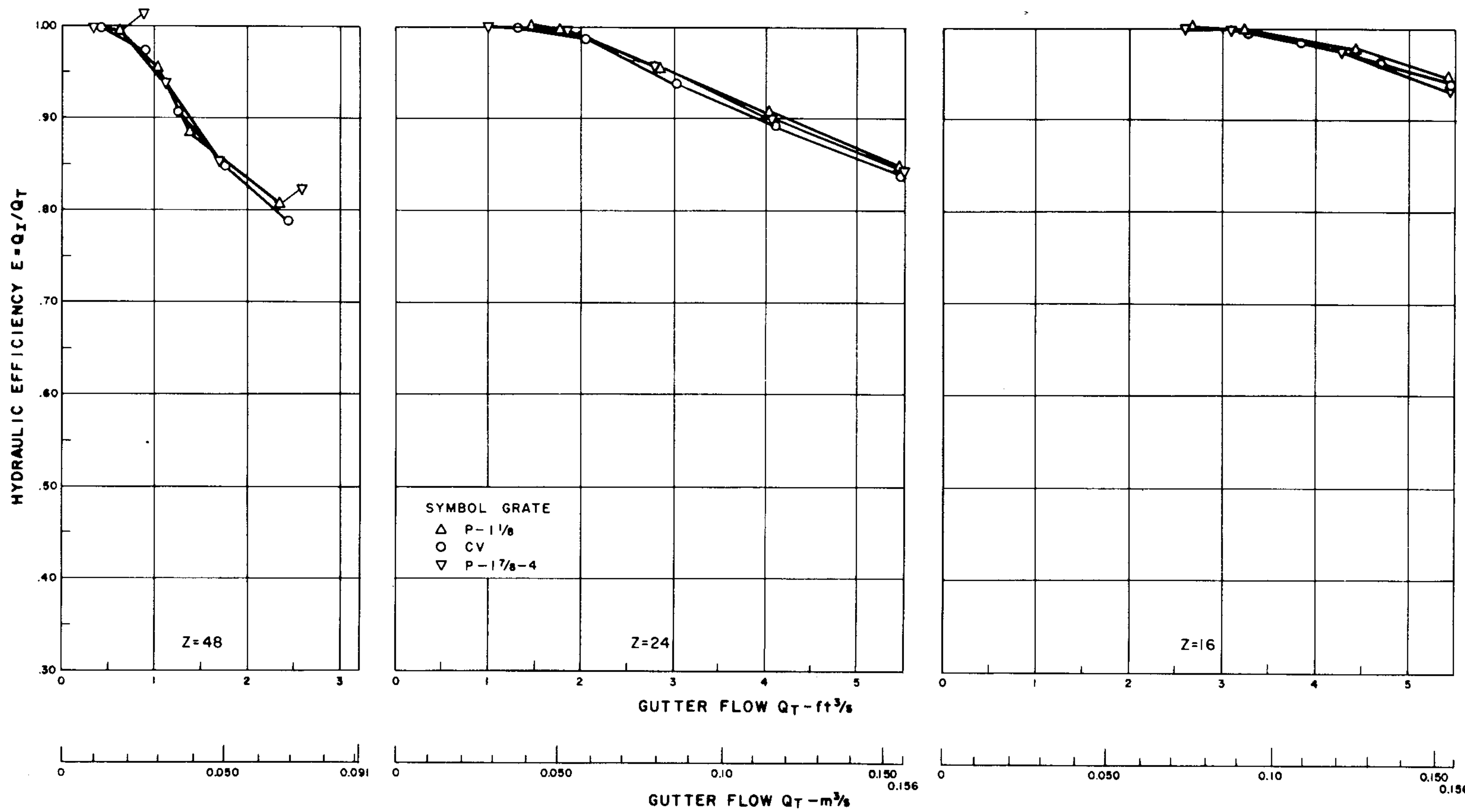


Figure 5-4. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 4.0 ft (0.91 m by 1.22 m) grates, S_0 = 4.0%.

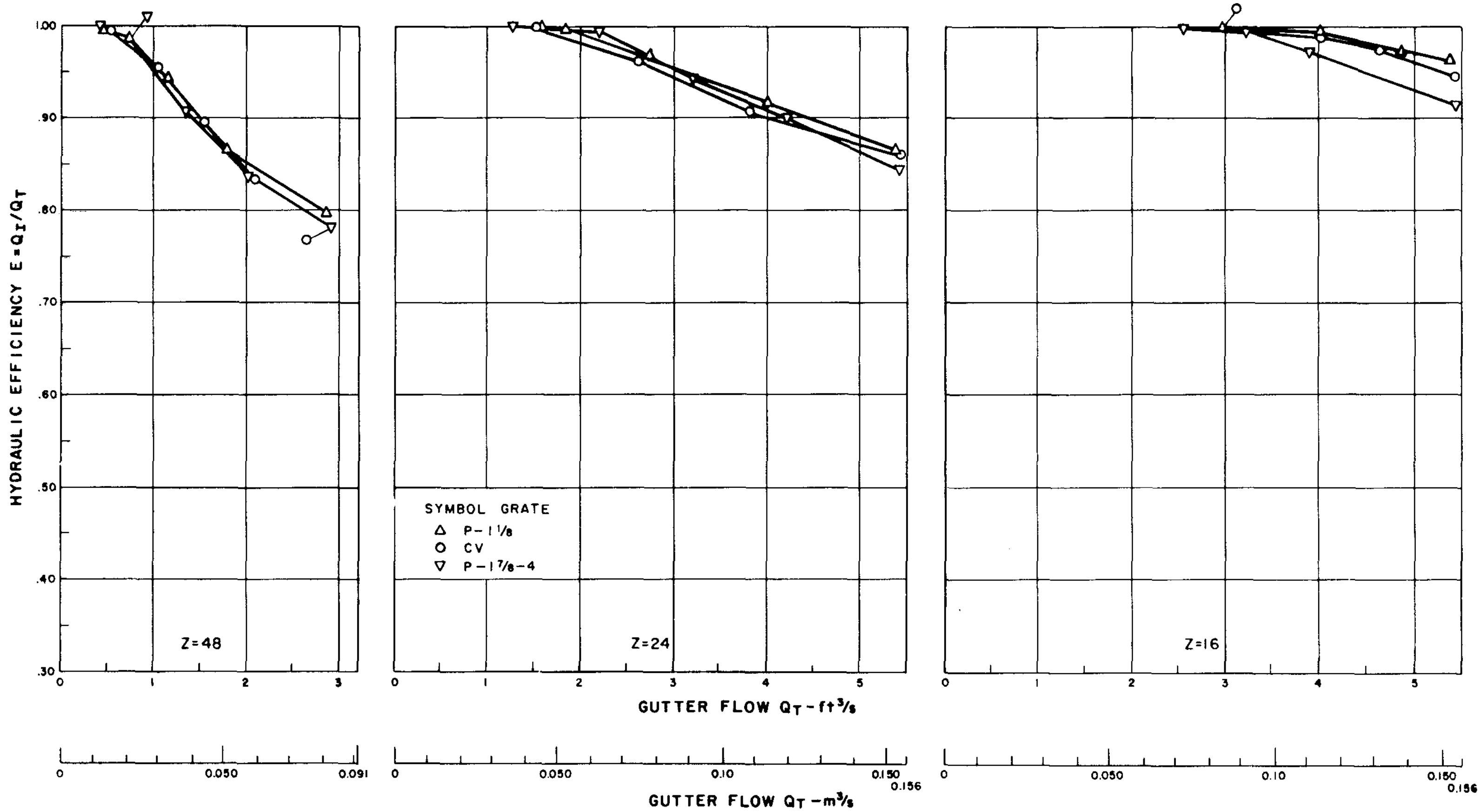


Figure 5-5. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 4.0 ft (0.91 m by 1.22 m) grates, S_0 = 6.0%.

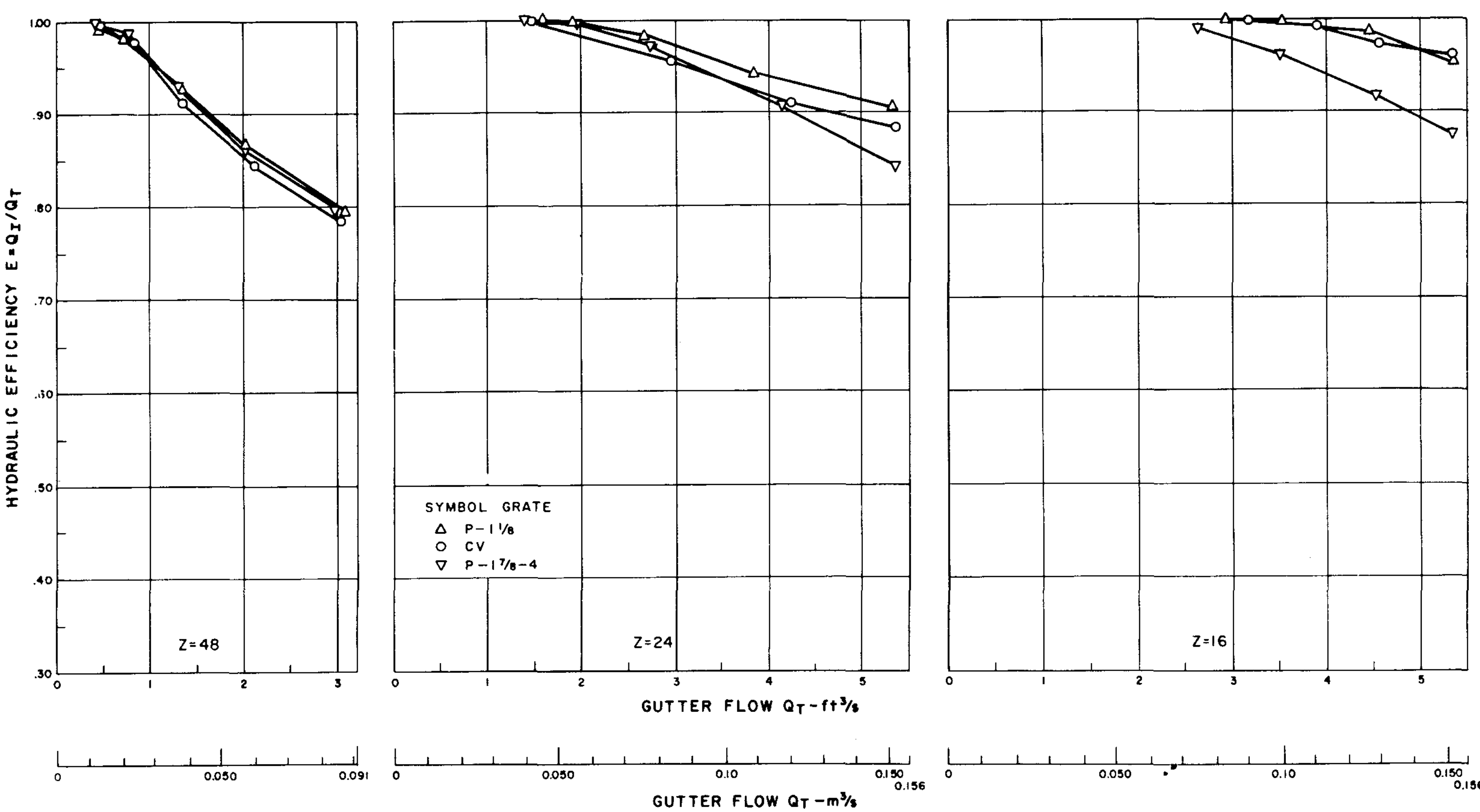


Figure 5-6. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 4.0 ft (0.91 m by 1.22 m) grates, S_0 = 9.0%.

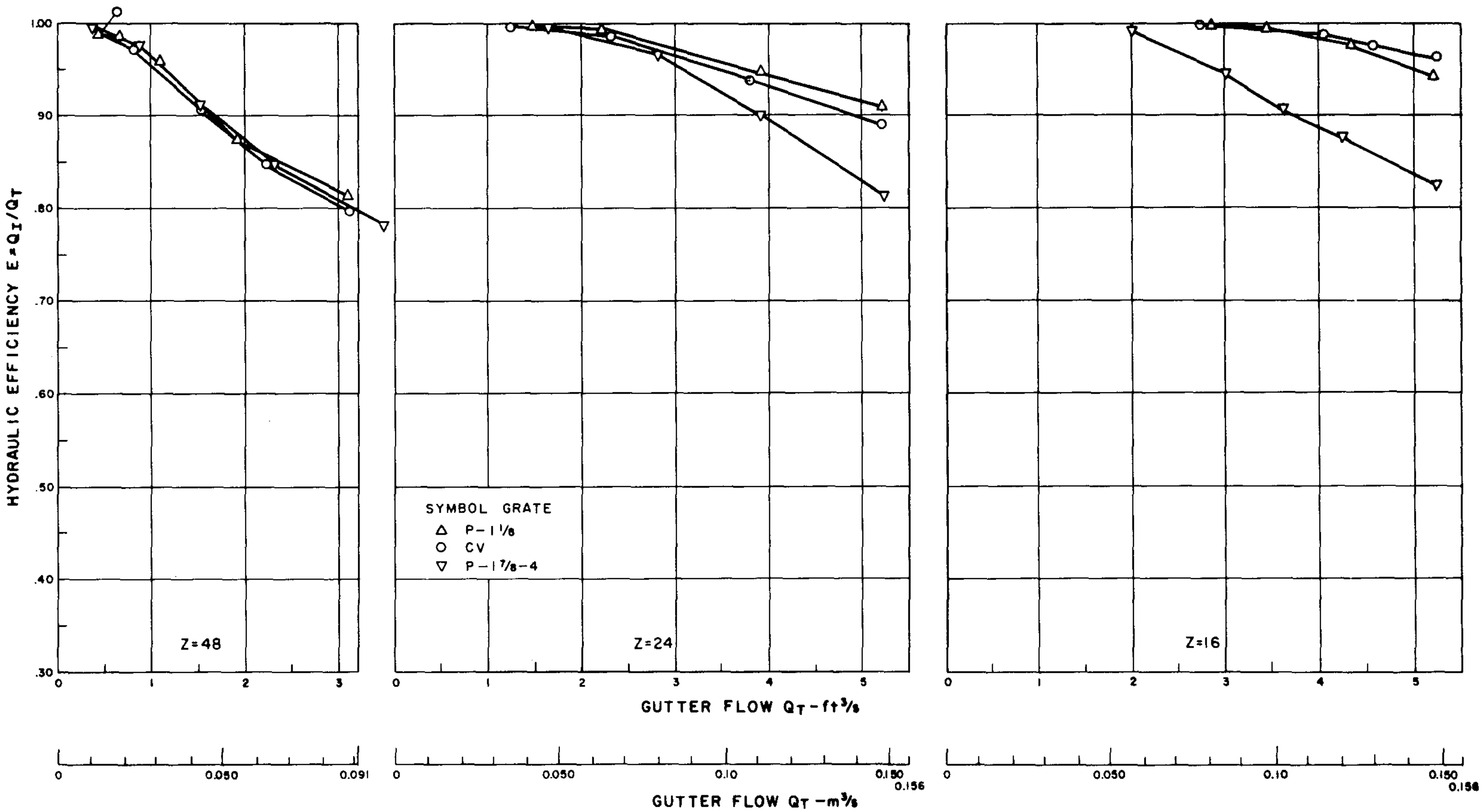


Figure 5-7. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 4.0 ft (0.91 m by 1.22 m) grates, S_0 = 13.0%.

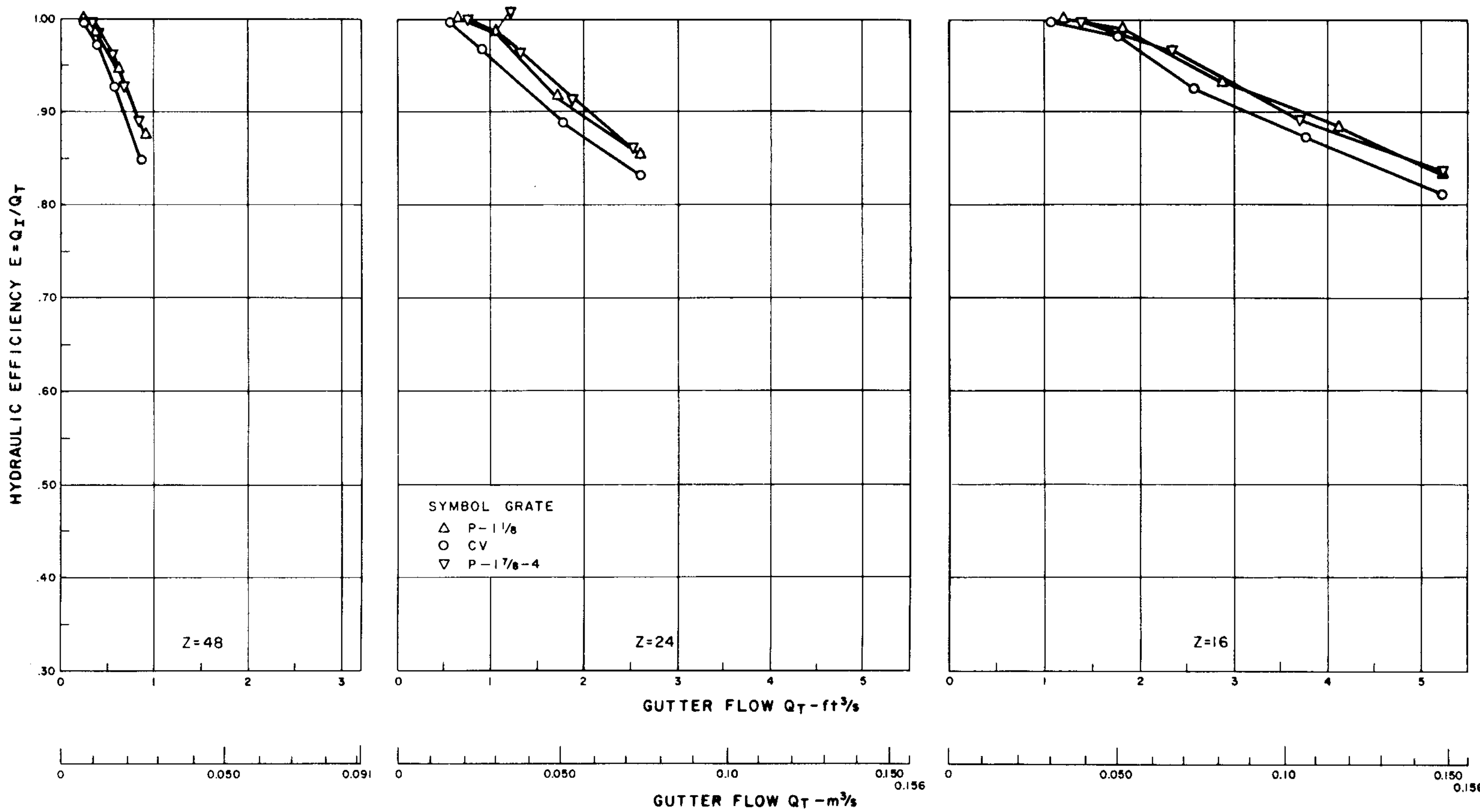


Figure 5-8. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates, $S_0 = 0.5\%$.

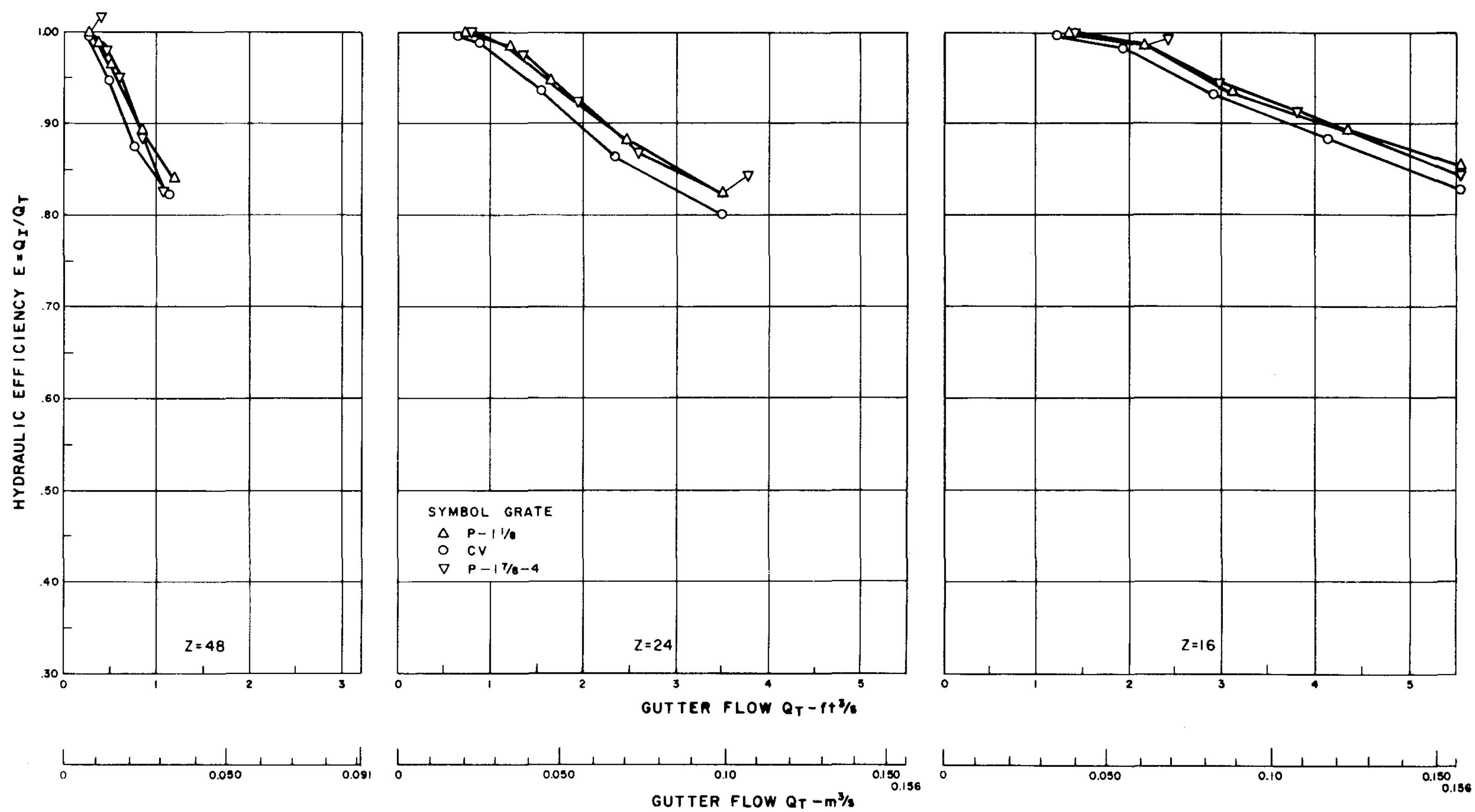


Figure 5-9. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates, S_0 = 1.0%.

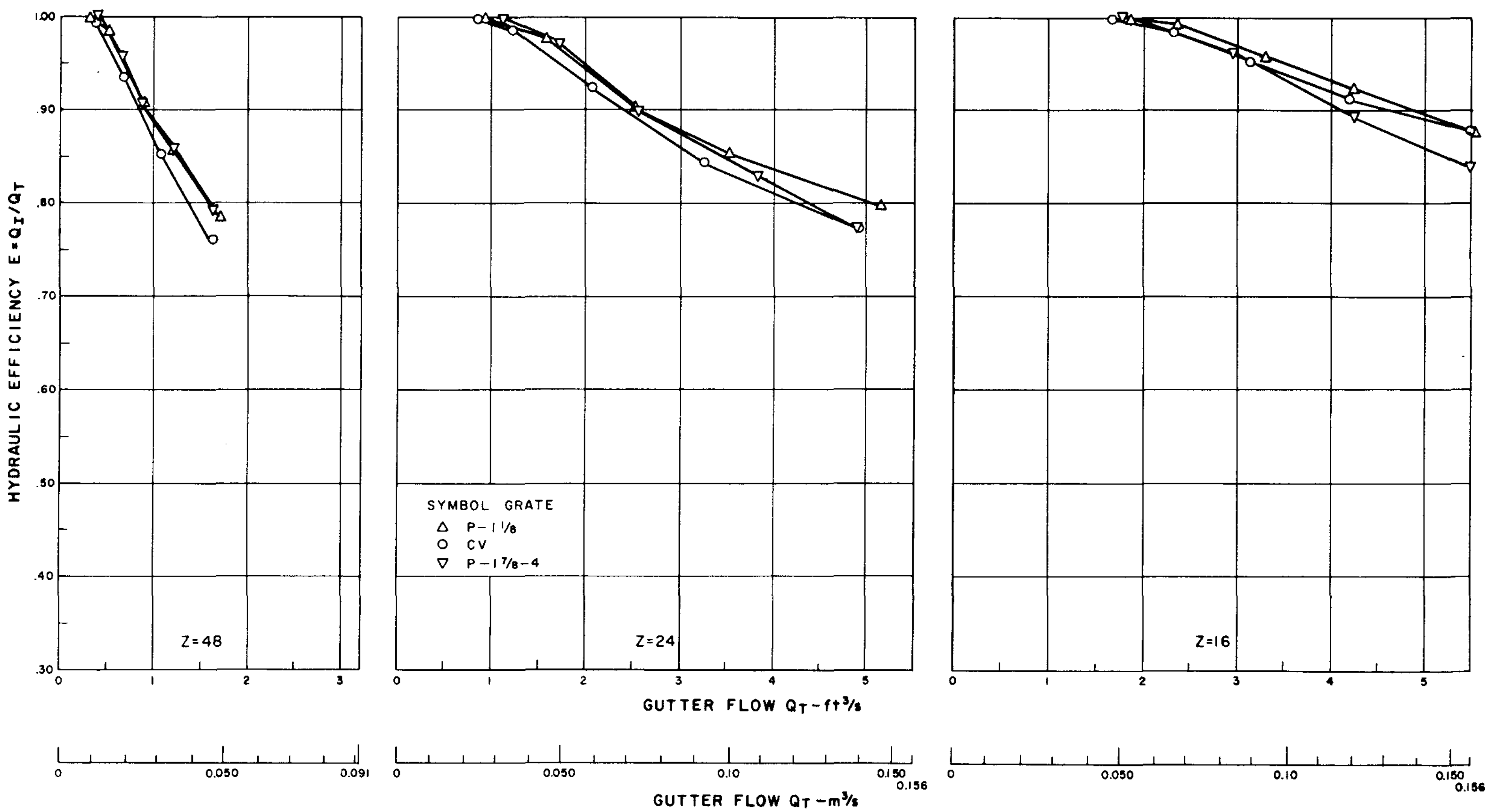


Figure 5-10. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates, S_0 = 2.0%.

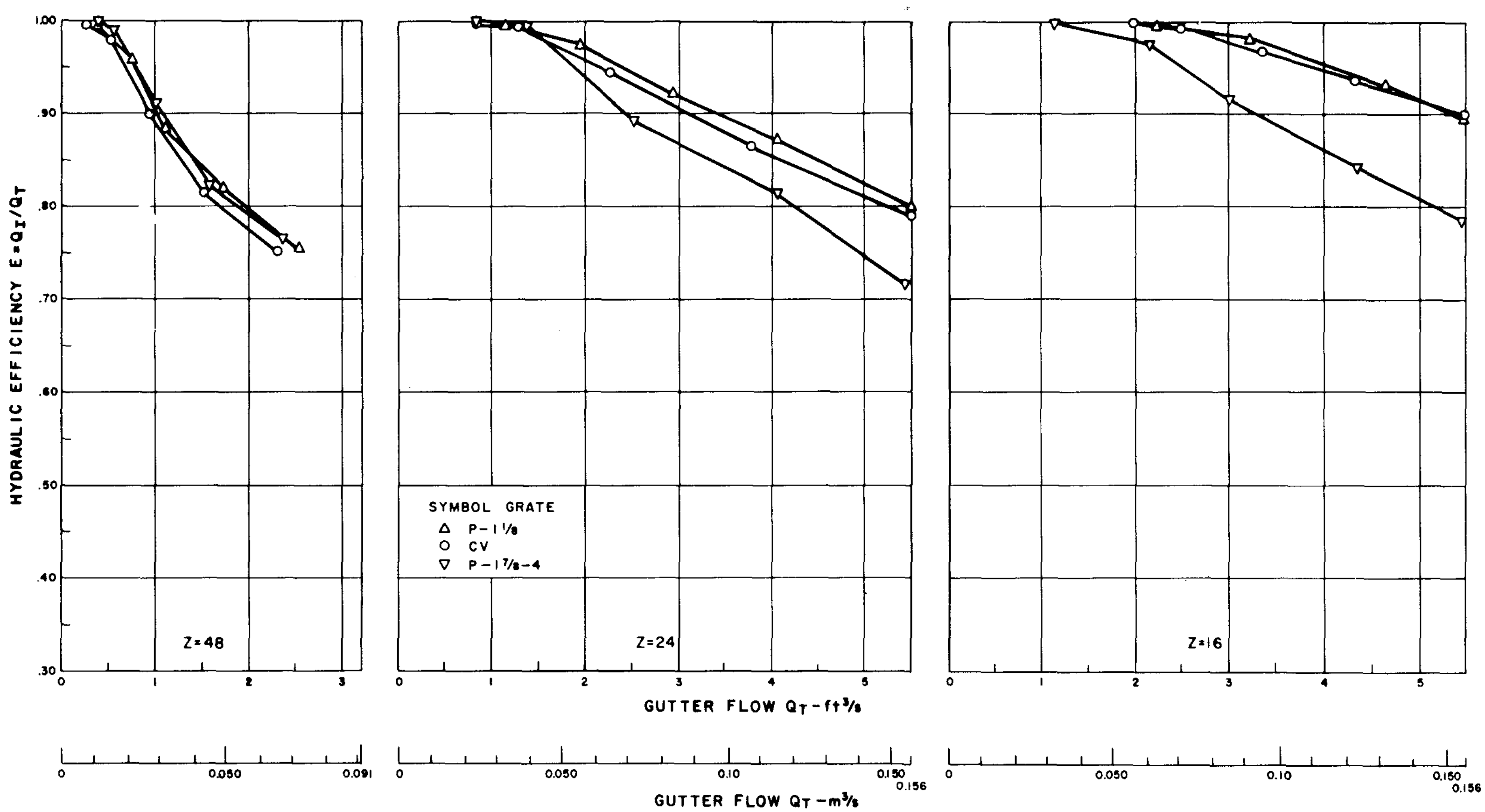


Figure 5-11. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates, S_0 = 4.0%.

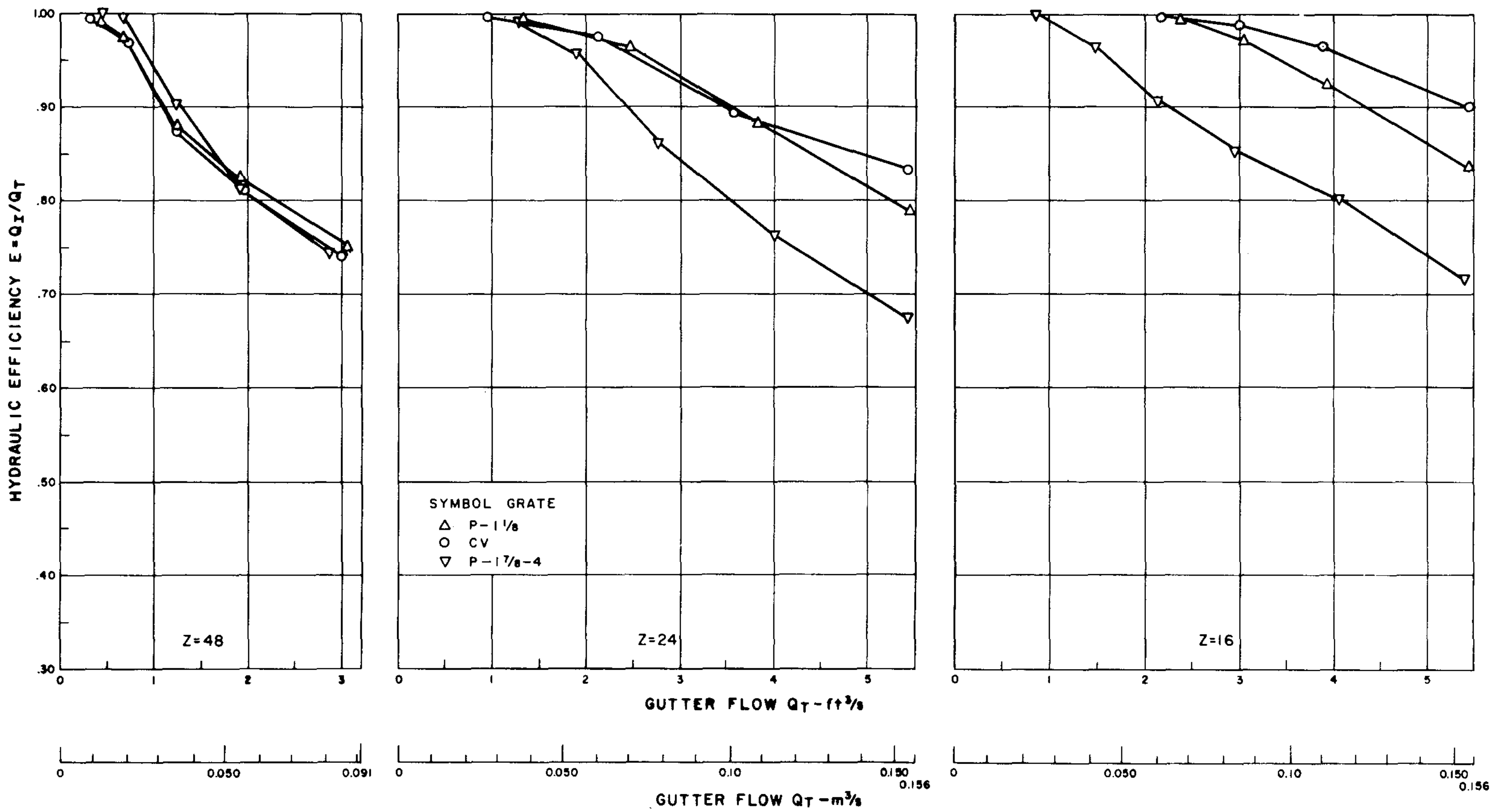


Figure 5-12. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates, S_0 = 6.0%.

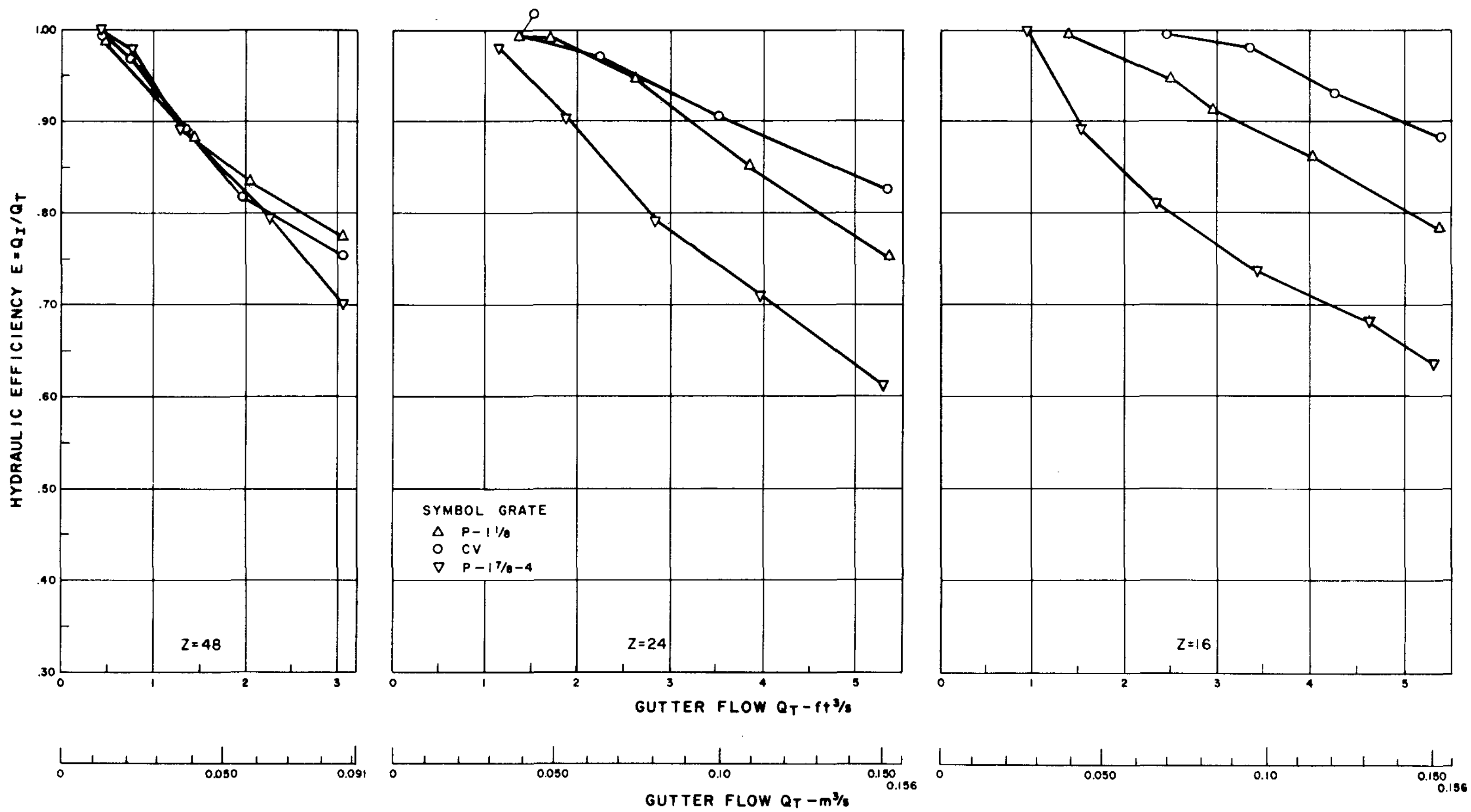


Figure 5-13. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates, S_0 = 9.0%.

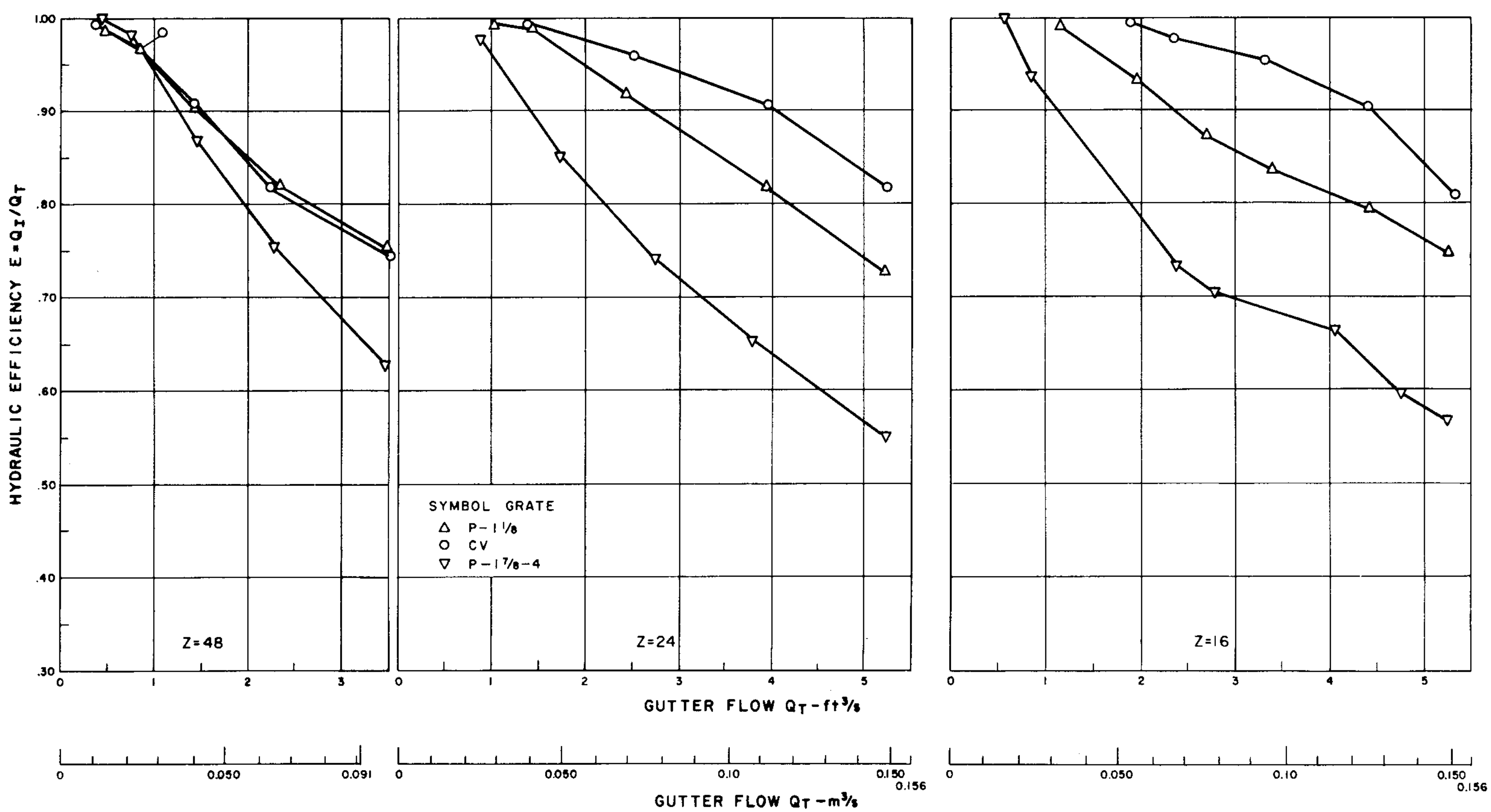


Figure 5-14. - Hydraulic efficiency vs. gutter flow for the 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates, S_0 = 13.0%.

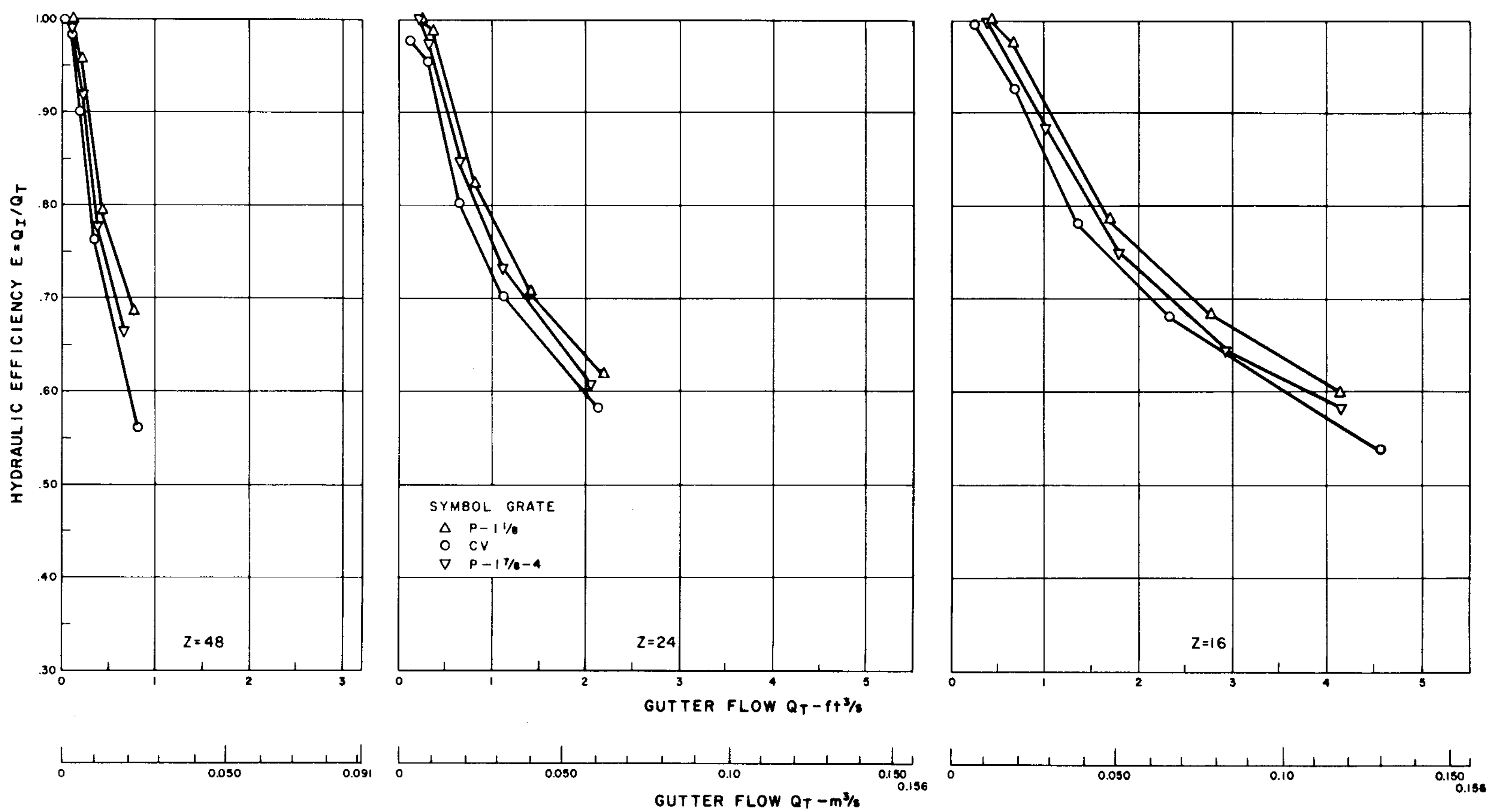


Figure 5-15. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.67 ft (0.38 m by 0.81 m) grates, S_0 = 0.5%.

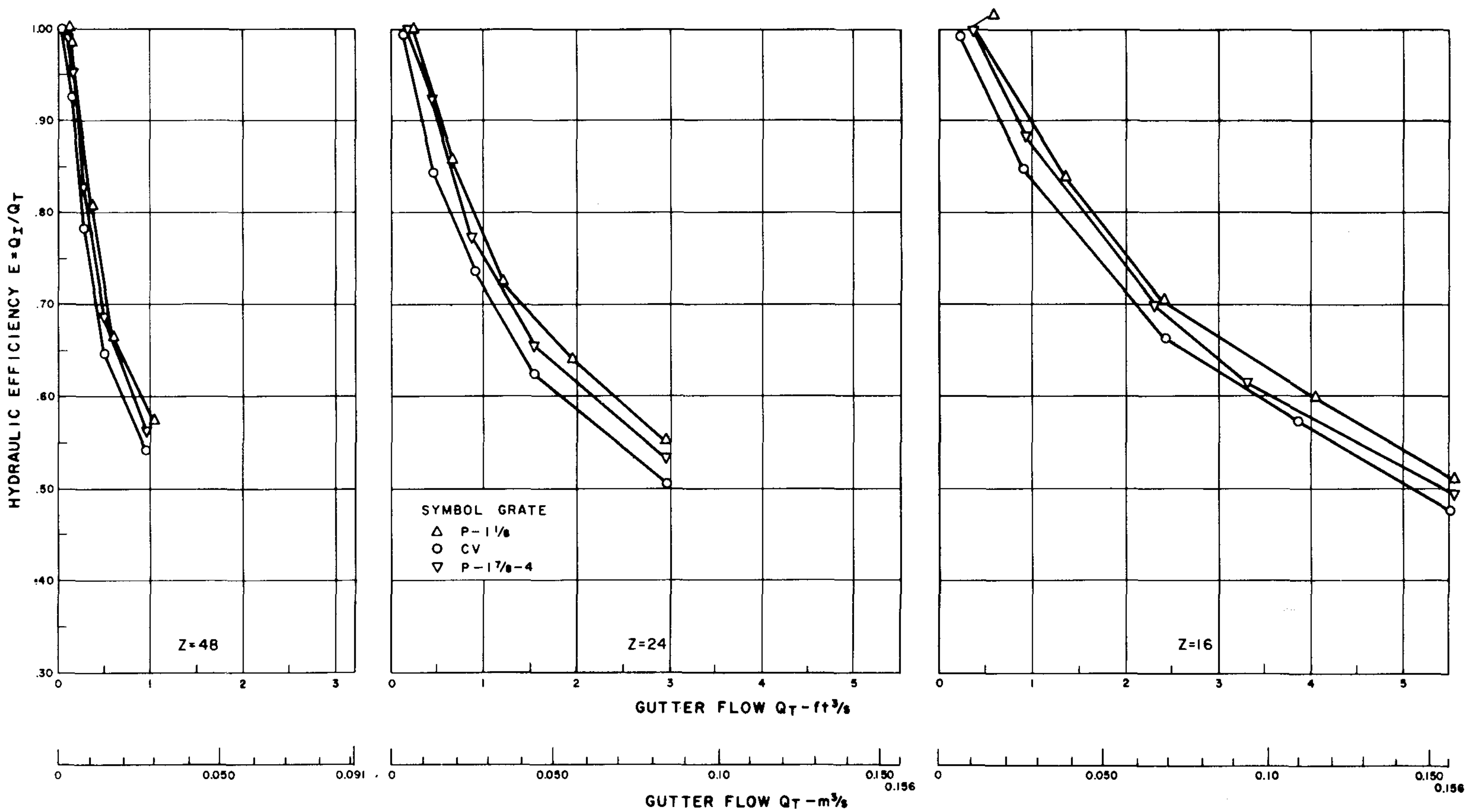


Figure 5-16. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.67 ft (0.38 m by 0.81 m) grates, S_0 = 1.0%.

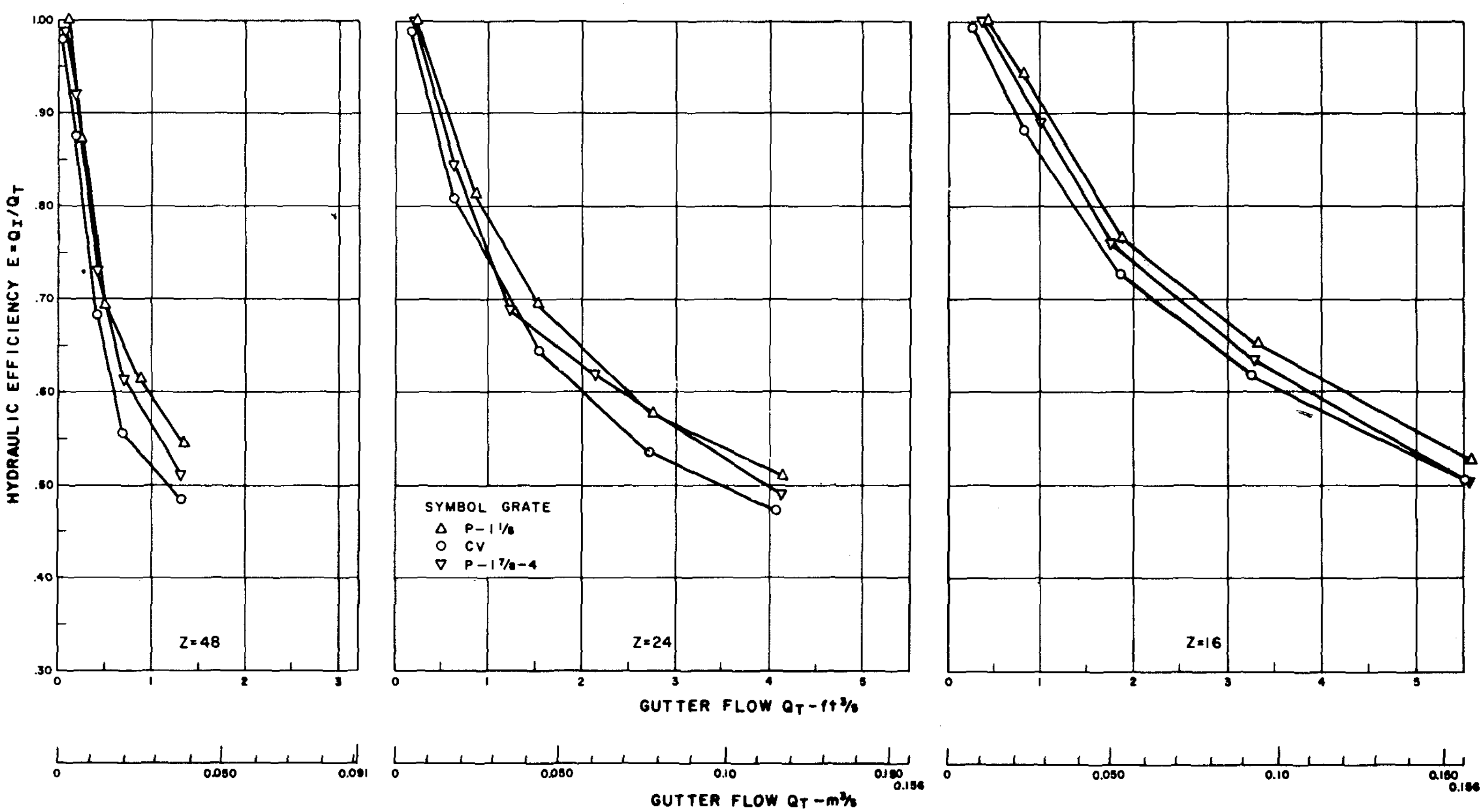


Figure 5-17. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.67 ft (0.38 m by 0.81 m) grates, S_0 = 2.0%.

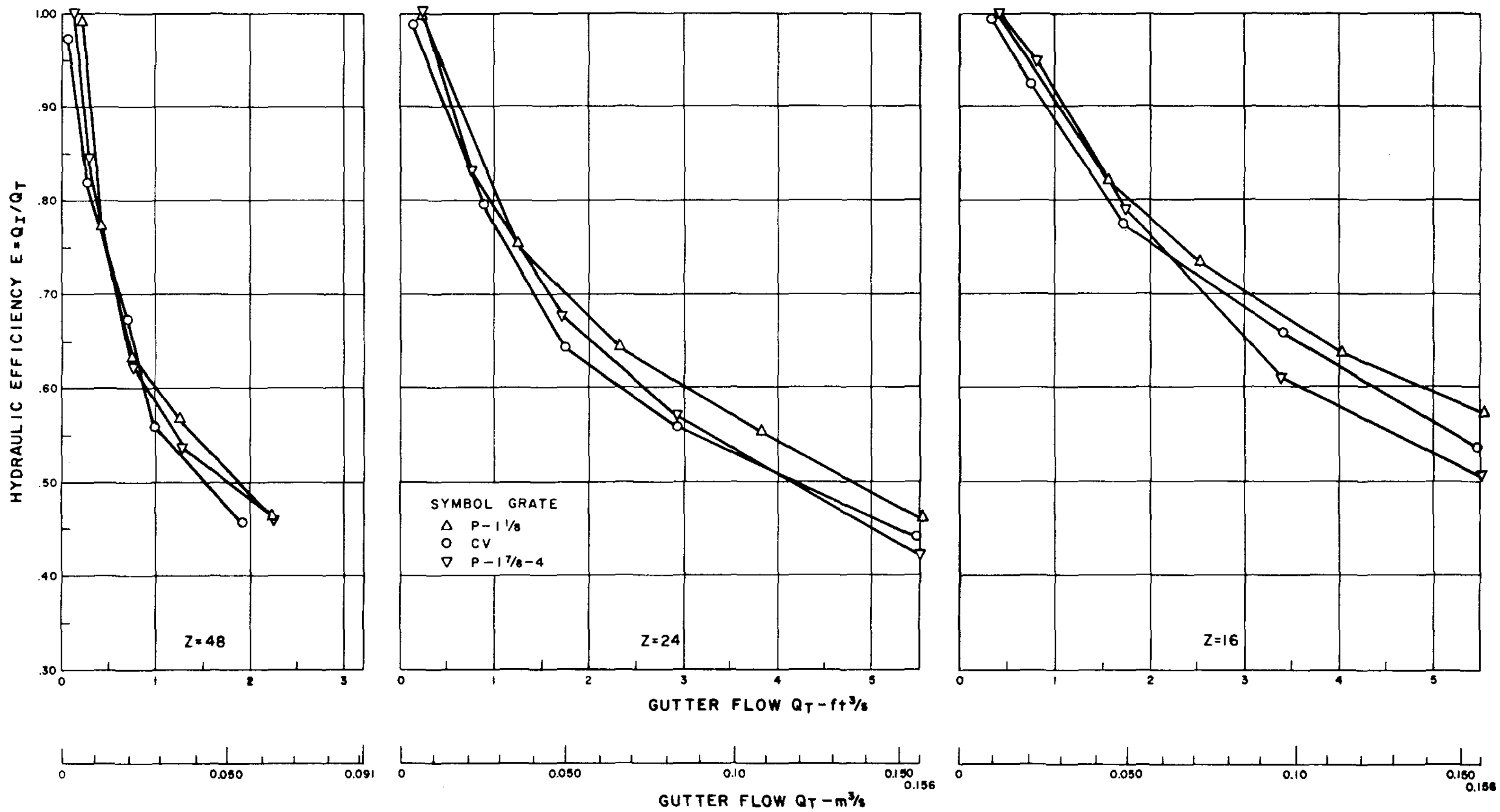


Figure 5-18. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.67 ft (0.38 m by 0.81 m) grates, S_0 = 4.0%.

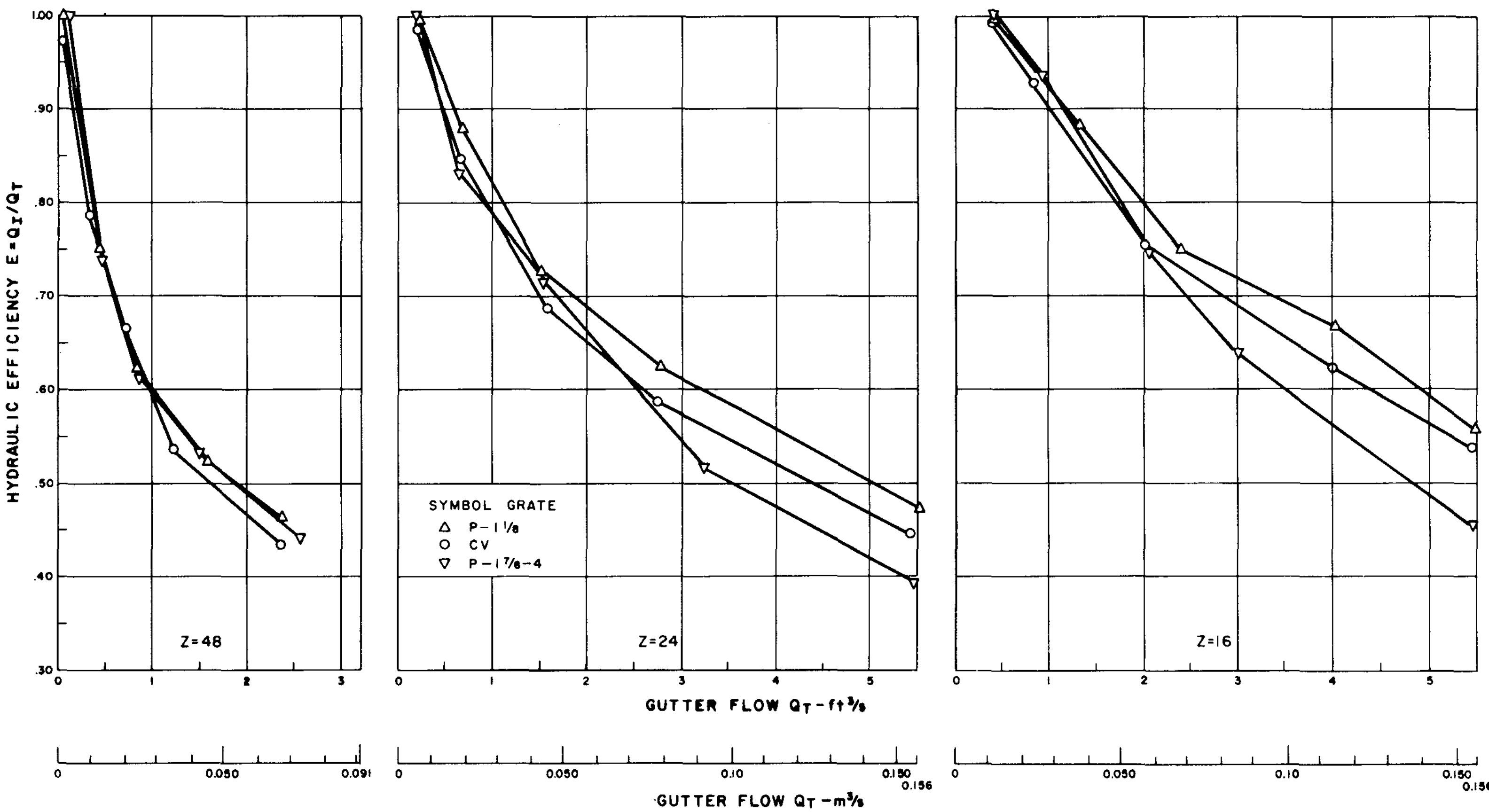


Figure 5-19. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.67 ft (0.38 m by 0.81 m) grates, S_0 = 6.0%.

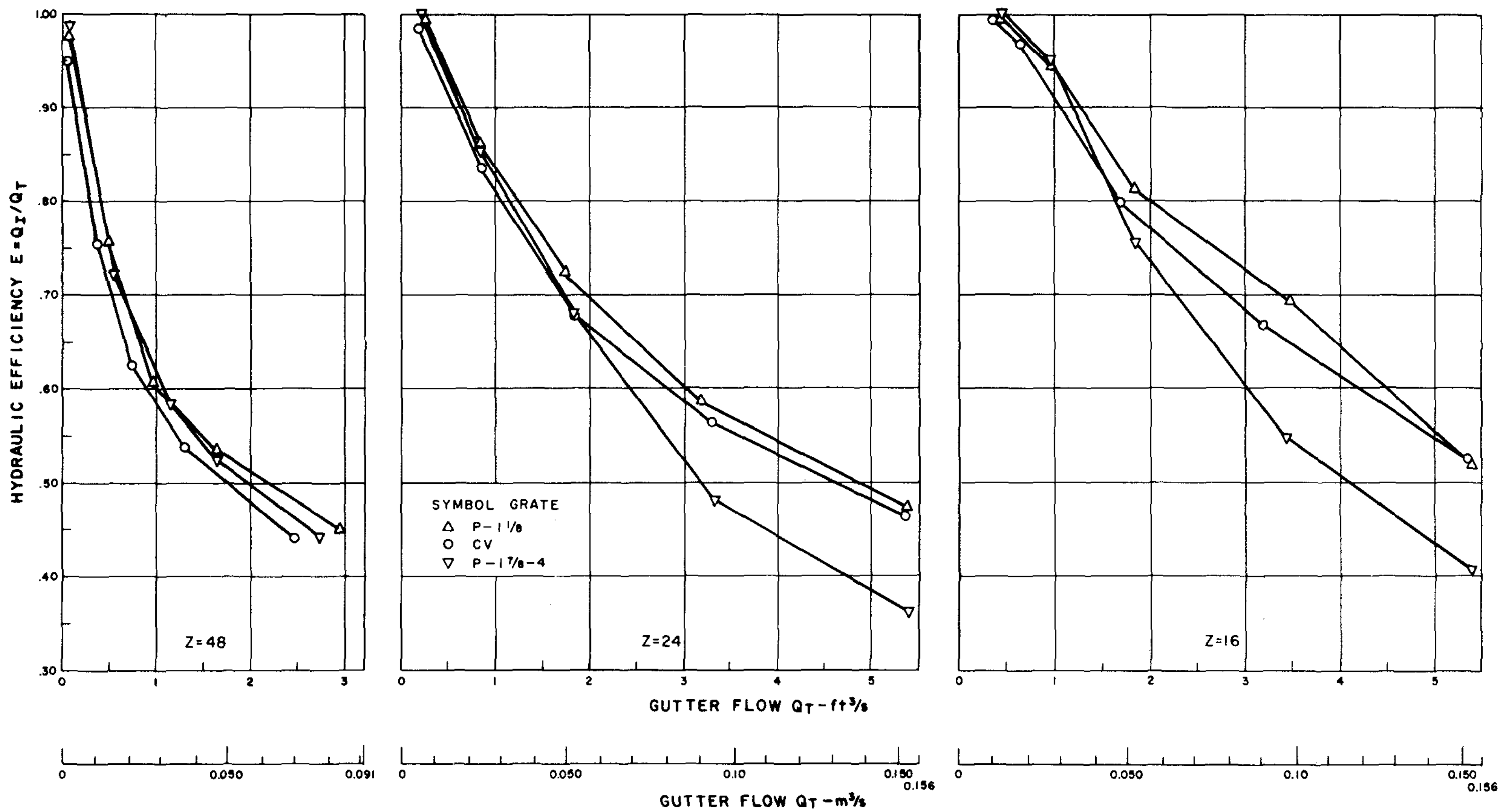


Figure 5-20. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.67 ft (0.38 m by 0.81 m) grates, S_0 = 9.0%.

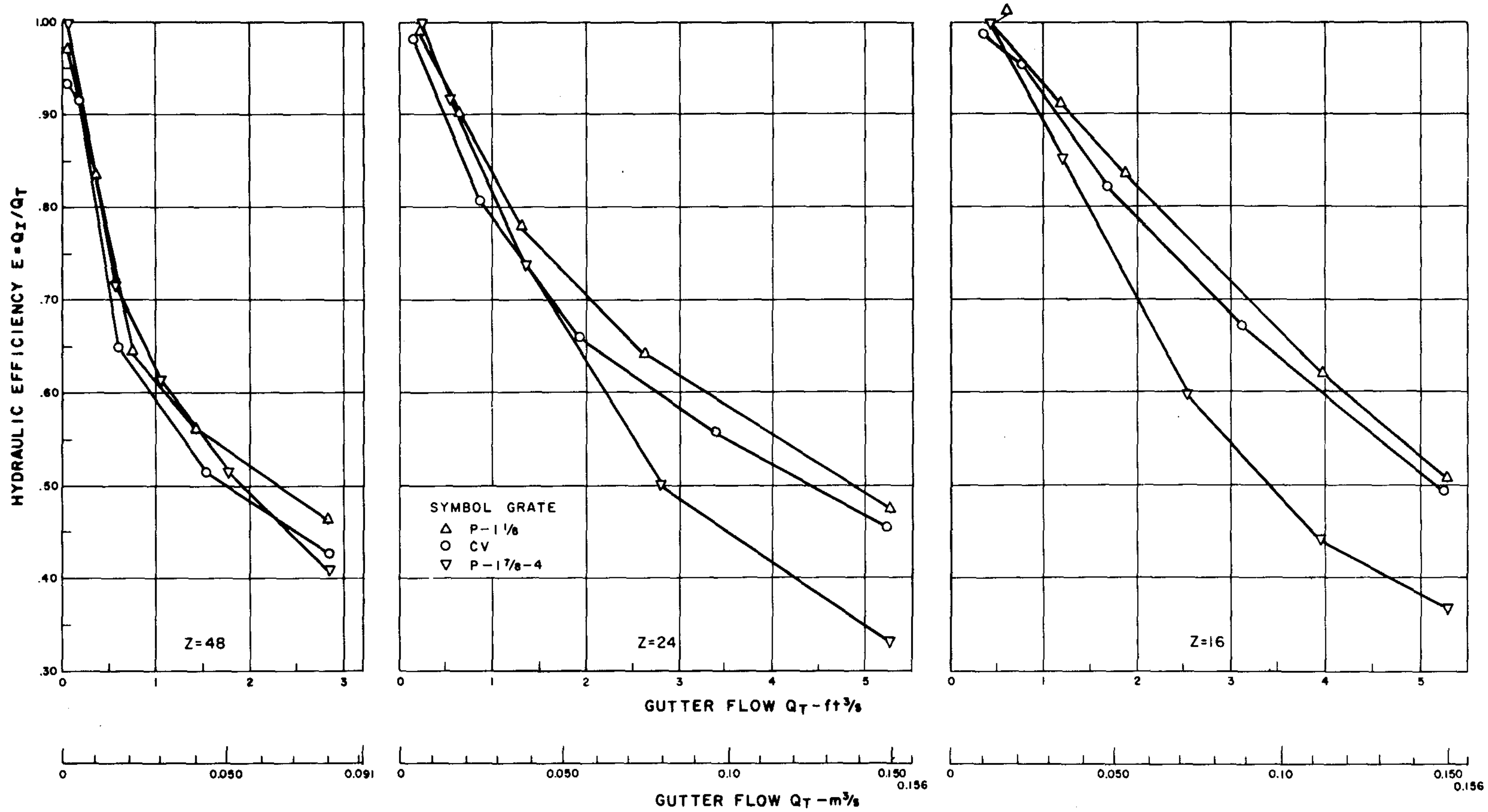


Figure 5-21. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.67 ft (0.38 m by 0.81 m) grates, S_0 = 13.0%.

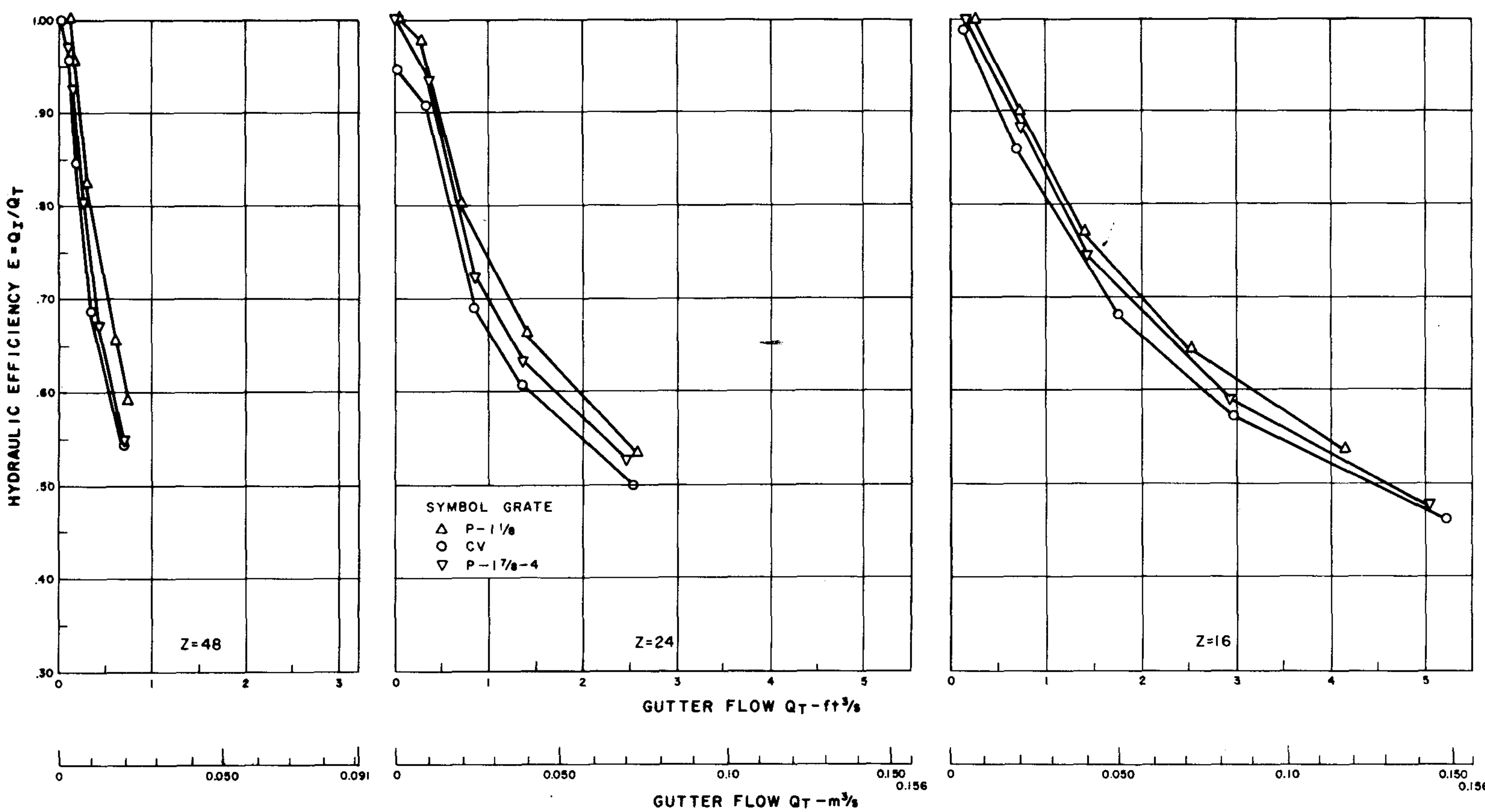


Figure 5-22. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grates, S_0 = 0.5%.

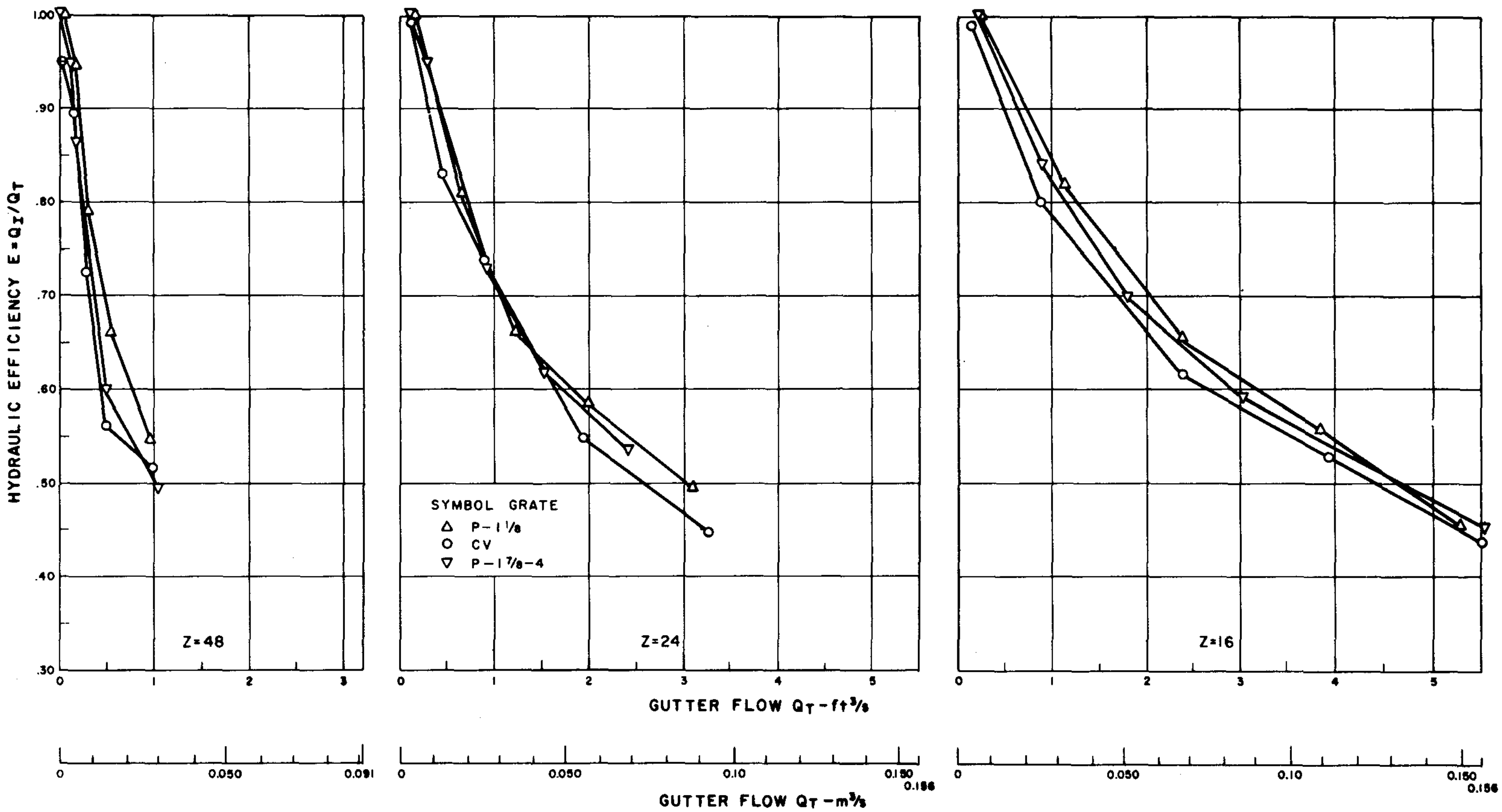


Figure 5-23. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grates, S_0 = 1.0%.

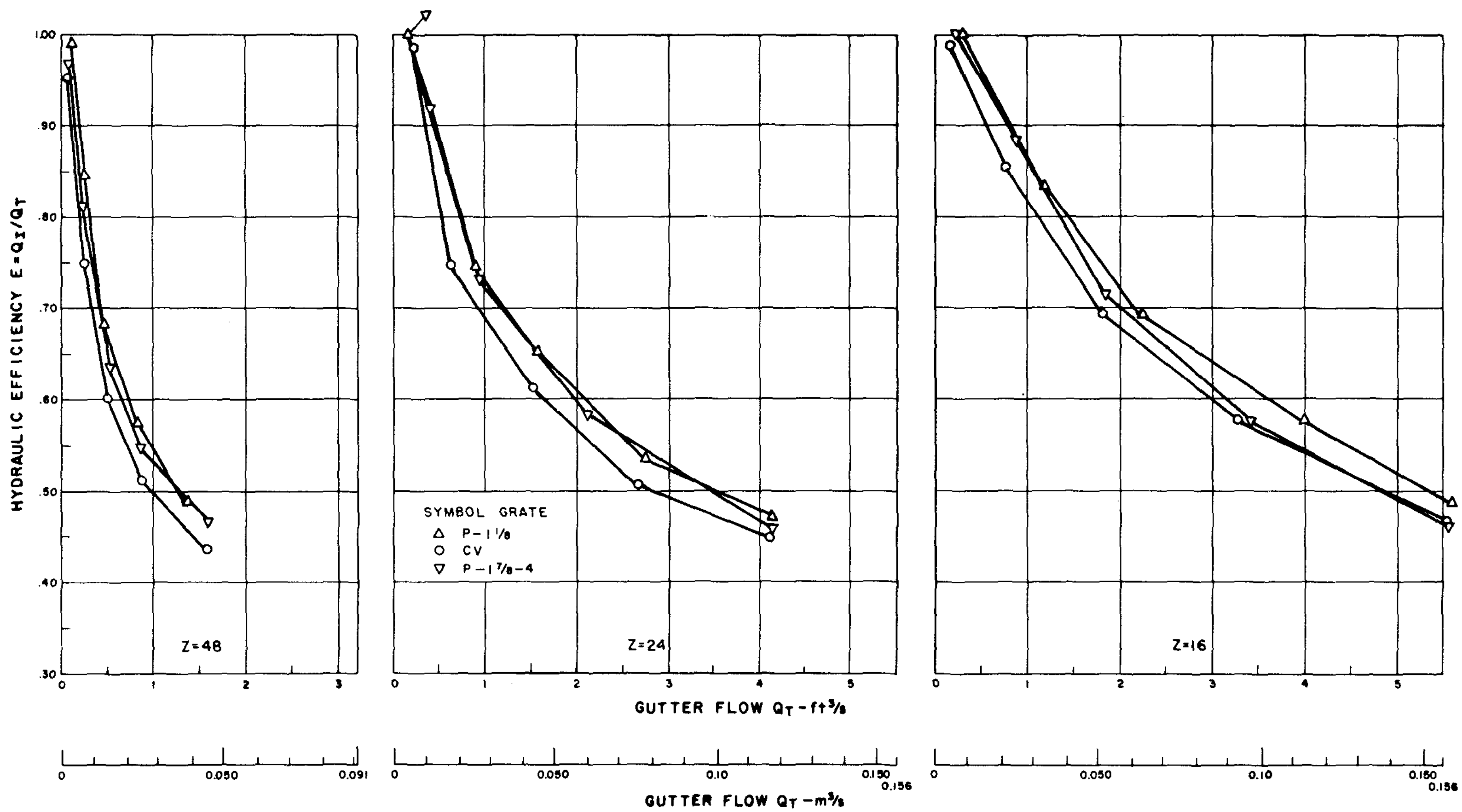


Figure 5-24. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grates, S_0 = 2.0%.

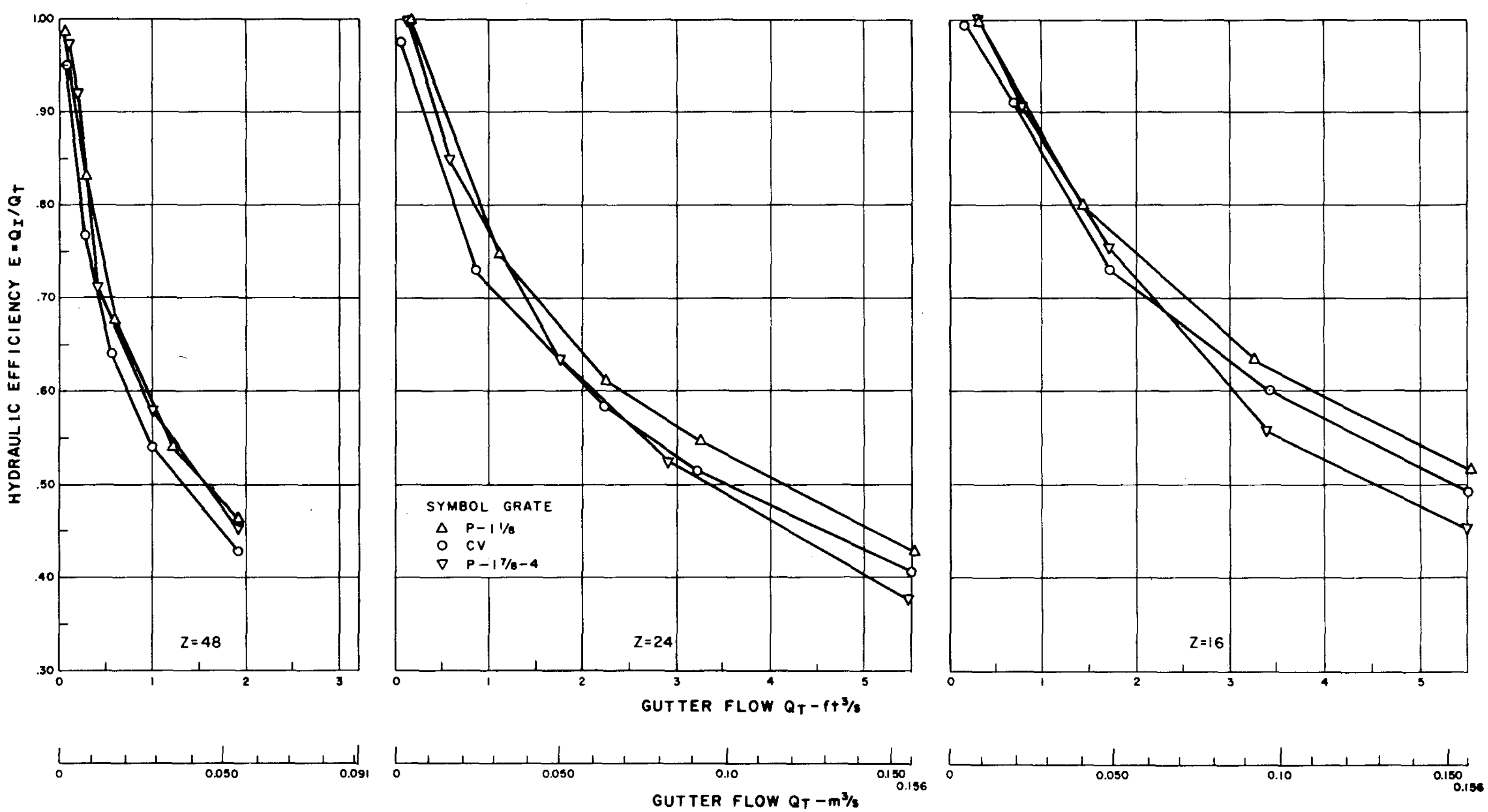


Figure 5-25. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grates, S_0 = 4.0%.

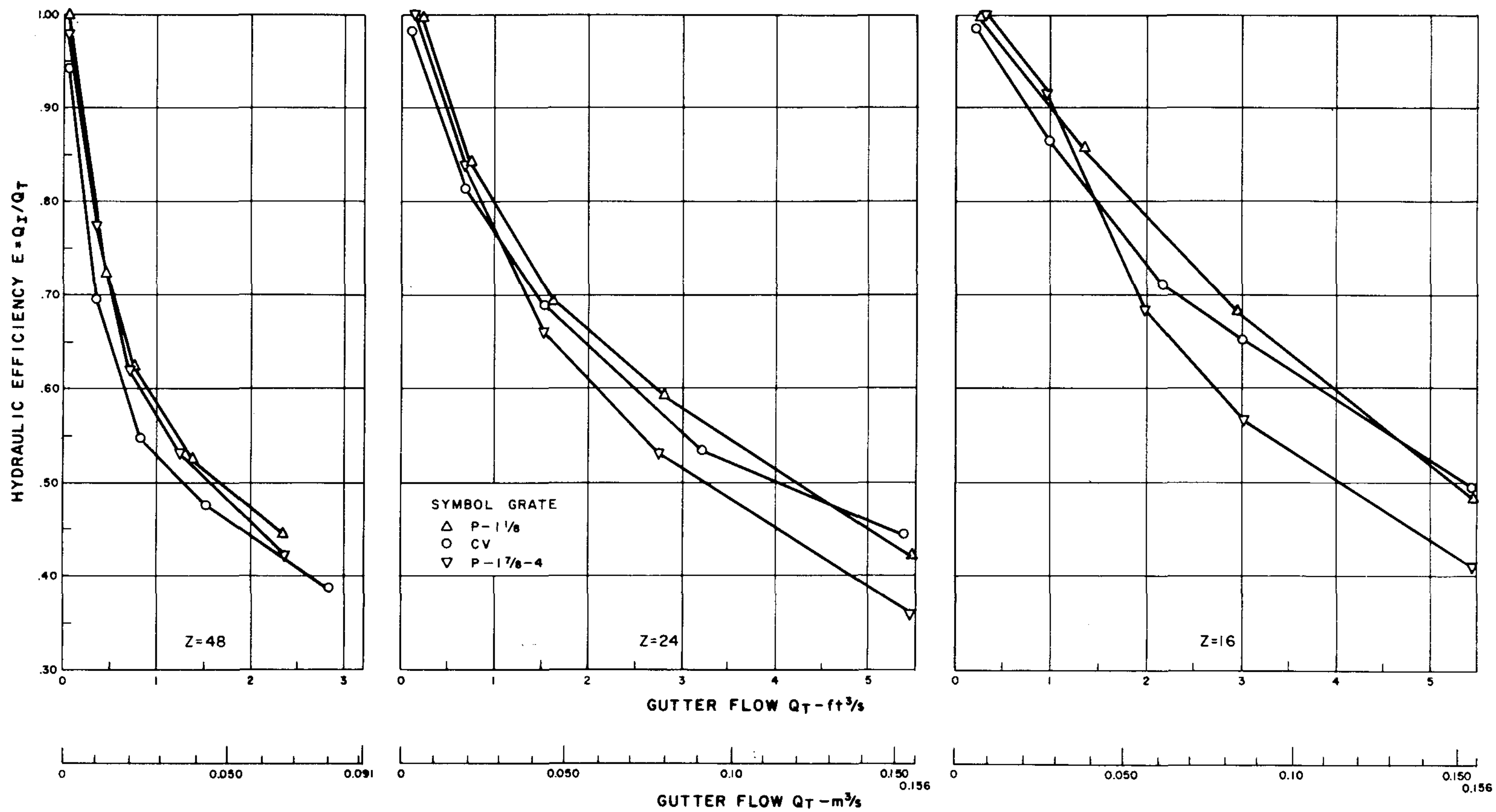


Figure 5-26. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grates, S_0 = 6.0%.

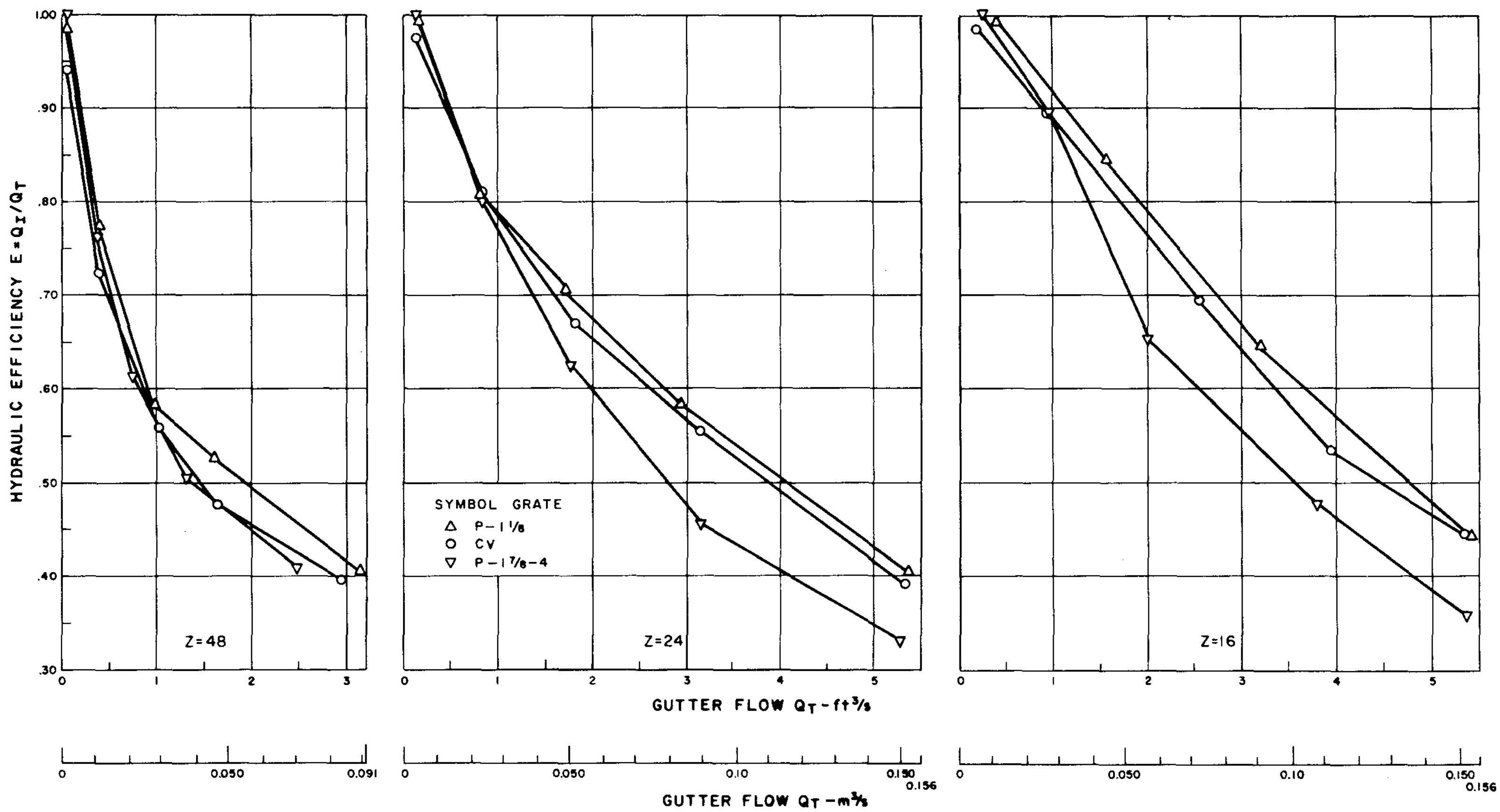


Figure 5-27. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grates, S_0 = 9.0%.

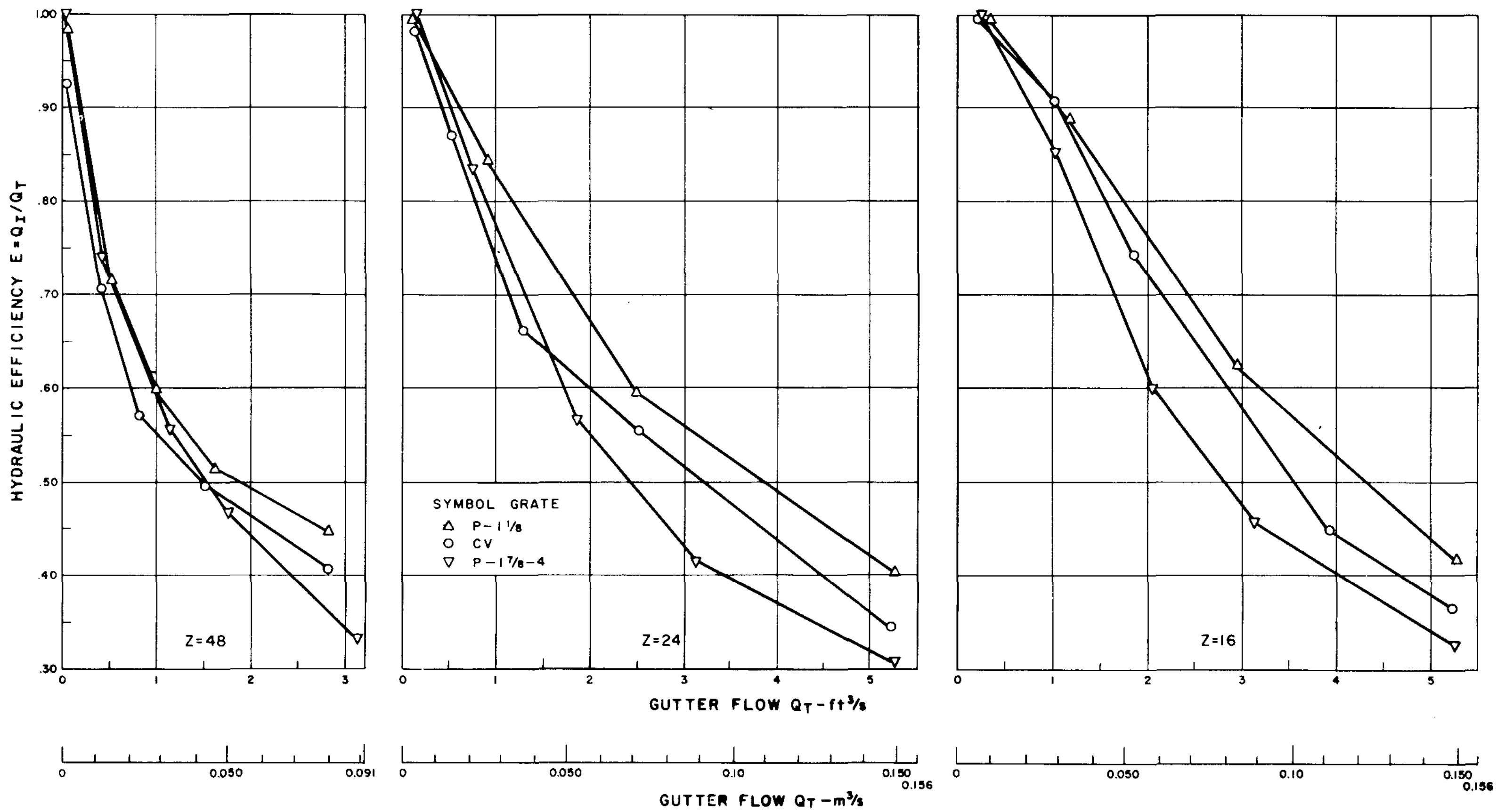


Figure 5-28. - Hydraulic efficiency vs. gutter flow for the 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grates, S_0 = 13.0%.

two grate designs. The exception is the 3.0 ft by 2.0 ft (0.91 m by 0.61 m) size grates, where due to the short length of the grates both the P - 1-7/8 - 4 and P - 1-1/8 have a larger amount of flow passing over the downstream end of the grate than the CV - 3-1/4 - 4-1/4 grate. This can best be illustrated by comparing the three grate designs with Q_T = 5.30 ft^3/s (0.15 m^3/s), S_0 = 13 percent, and 1/Z = 1/16 in figure 5-29. For longitudinal slopes, S_0, of 4 percent or less the P - 1-1/8 grate is more efficient than the CV - 3-1/4 - 4-1/4 for the 3 ft by 2 ft (0.91 m by 0.61 m) size.

For longitudinal slope, S_0, greater than 2 percent the P - 1-7/8 - 4 grate is the least efficient. For S_0 < 2 percent the CV - 3-1/4 - 4-1/4 grate is the least efficient due to its smaller effective inlet area.

Figures 5-30 through 5-47 compare the performance of the three grate designs for a given size, width of spread, T', and cross slope, 1/Z, as the longitudinal slope, S_0, varies from 0.5 to 13.0 percent. The 2.0 ft by 2.0 ft (0.61 m by 0.61 m) and 2.0 ft by 4.0 ft (0.61 m by 1.22 m) size grates from volume 1 are also included. The width of spread, T', selected for each cross slope is near the maximum tested on the hydraulic facility. The values for T' were 4.5, 5.5, and 7.0 ft (1.37, 1.68, and 2.13 m) for the cross slope values of 1/Z = 1/16, 1/24, and 1/48.

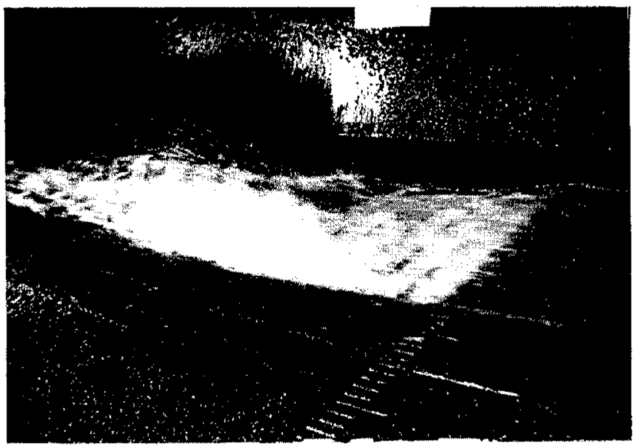
For cross slope conditions of 1/Z = 1/16, the P - 1-1/8 and CV - 3-1/4 - 4-1/4 grates are hydraulically superior for all six grate sizes when S_0 > 4 percent. For S_0 < 4 percent the CV - 3-1/4 - 4-1/4 has the lowest hydraulic efficiency due to its smaller effective inlet area. Similar trends are observed for figures 5-36 through 5-47 where 1/Z = 1/24 and 1/48.

Conclusions

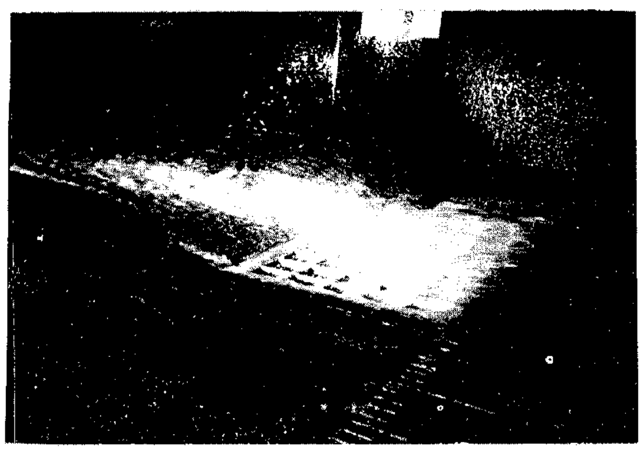
This volume presents the results of the extension of the studies described in volume 1. The purpose of these additional tests was to broaden the available design data for grate inlet widths other than the 2 ft (0.61 m) width used in volume 1. Based on the recommendations of volume 1 the three best grate inlets were selected for further tests using grate inlet widths of 1.25 ft and 3.0 ft (0.38 m and 0.91 m). Two fabricated steel parallel bar grates were selected (one had transverse bars at the surface and the other, small spacers), and a cast iron curved vane grate. Information dealing with the structural integrity, safety, and debris handling characteristics of these three grates can be found in volume 1.

In general for the higher energy gutter flow conditions (for 1/Z = 1/16 S_0 > 4%, for 1/Z = 1/24 S_0 > 6%, and for 1/Z = 1/48 S_0 > 13%) the P - 1-1/8 and the CV - 3-1/4 - 4-1/4 grate inlets are more

a. P - 1-1/8 grate inlet



b. P - 1-7/8 - 4 grate inlet



c. CV - 3-1/4 - 4-1/4 grate inlet

Figure 5-29. - Flow characteristics for the 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates; Q_T = 5.30 ft^3/s (0.15 m^3/s), S_0 = 13%, Z = 16. Photo 1765-441

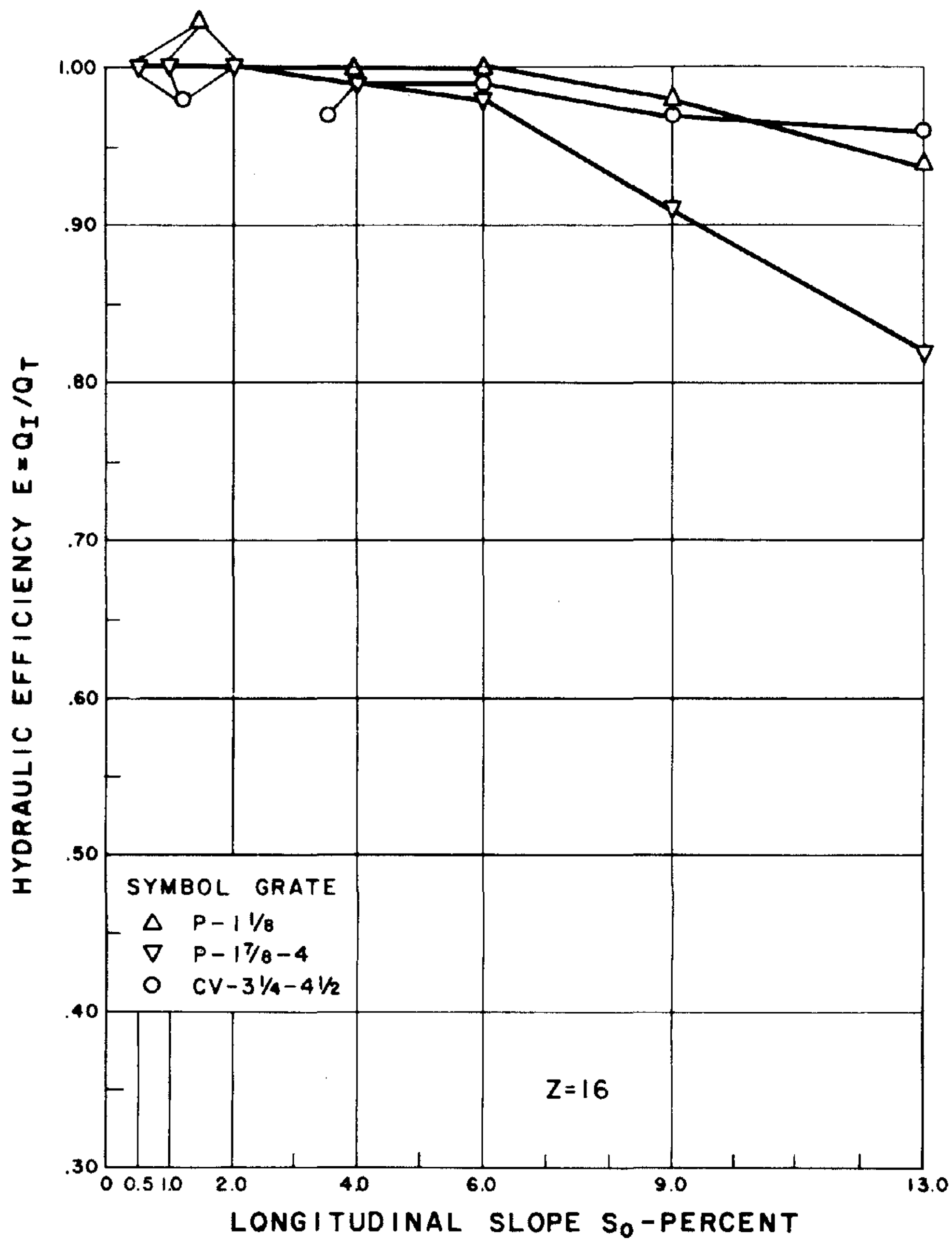


Figure 5-30. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 4.5 ft (1.37 m), Z = 16, 3.0 ft by 4.0 ft (0.91 m by 1.22 m) grates.

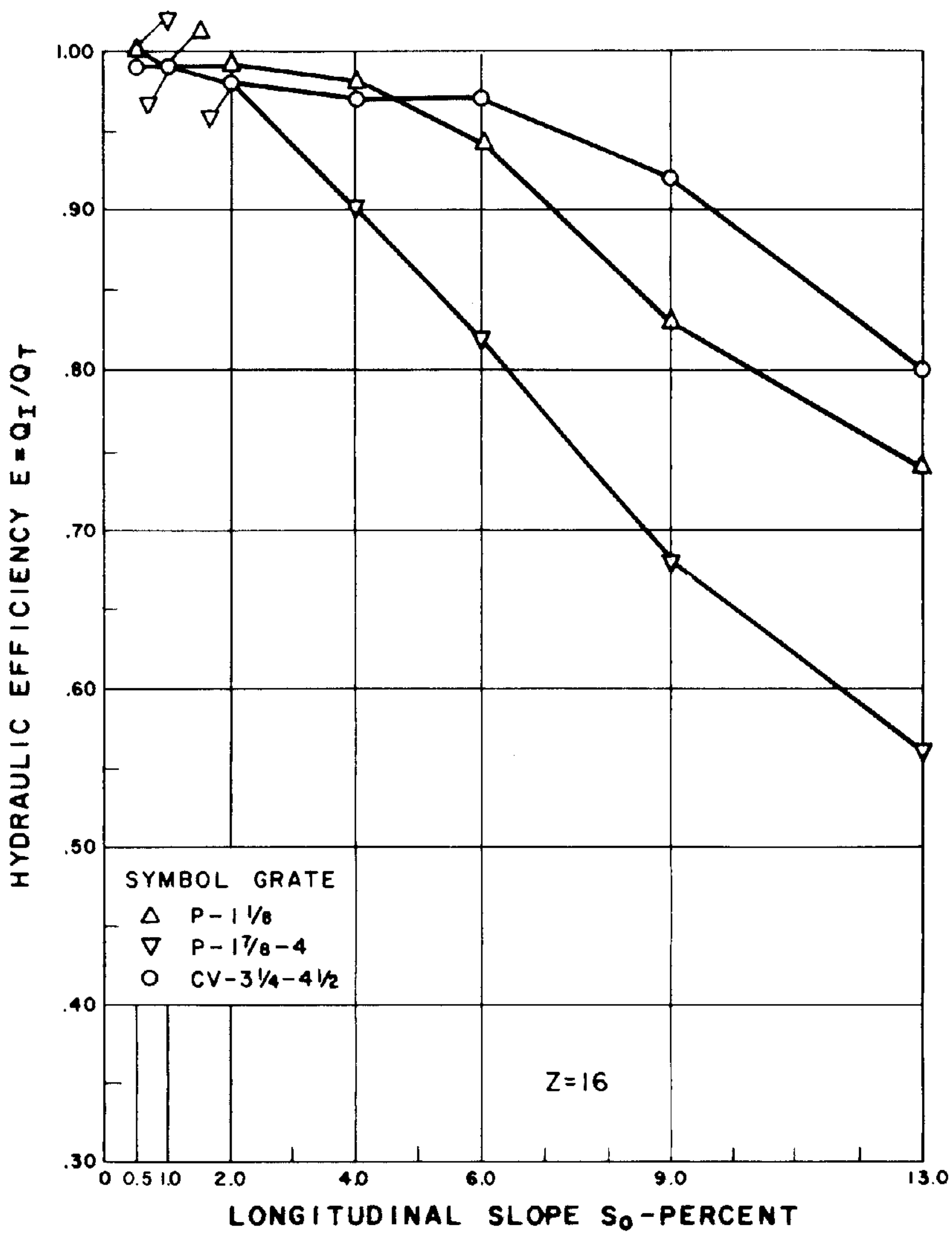


Figure 5-31. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 4.5 ft (1.37 m), Z = 16, 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates.

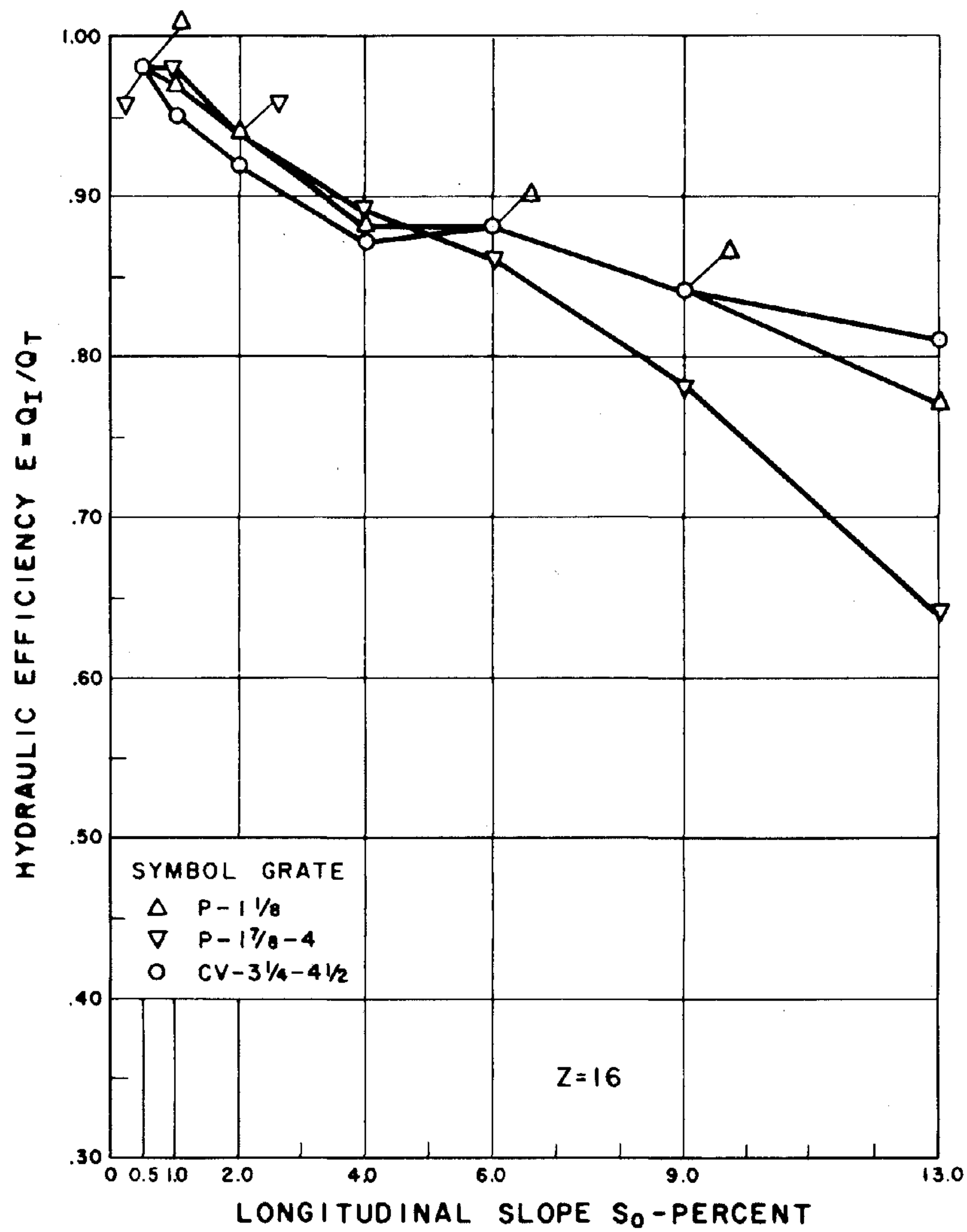


Figure 5-32. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 4.5 ft (1.37 m), Z = 16, 2.0 ft by 4.0 ft (0.61 m by 1.22 m) grates.

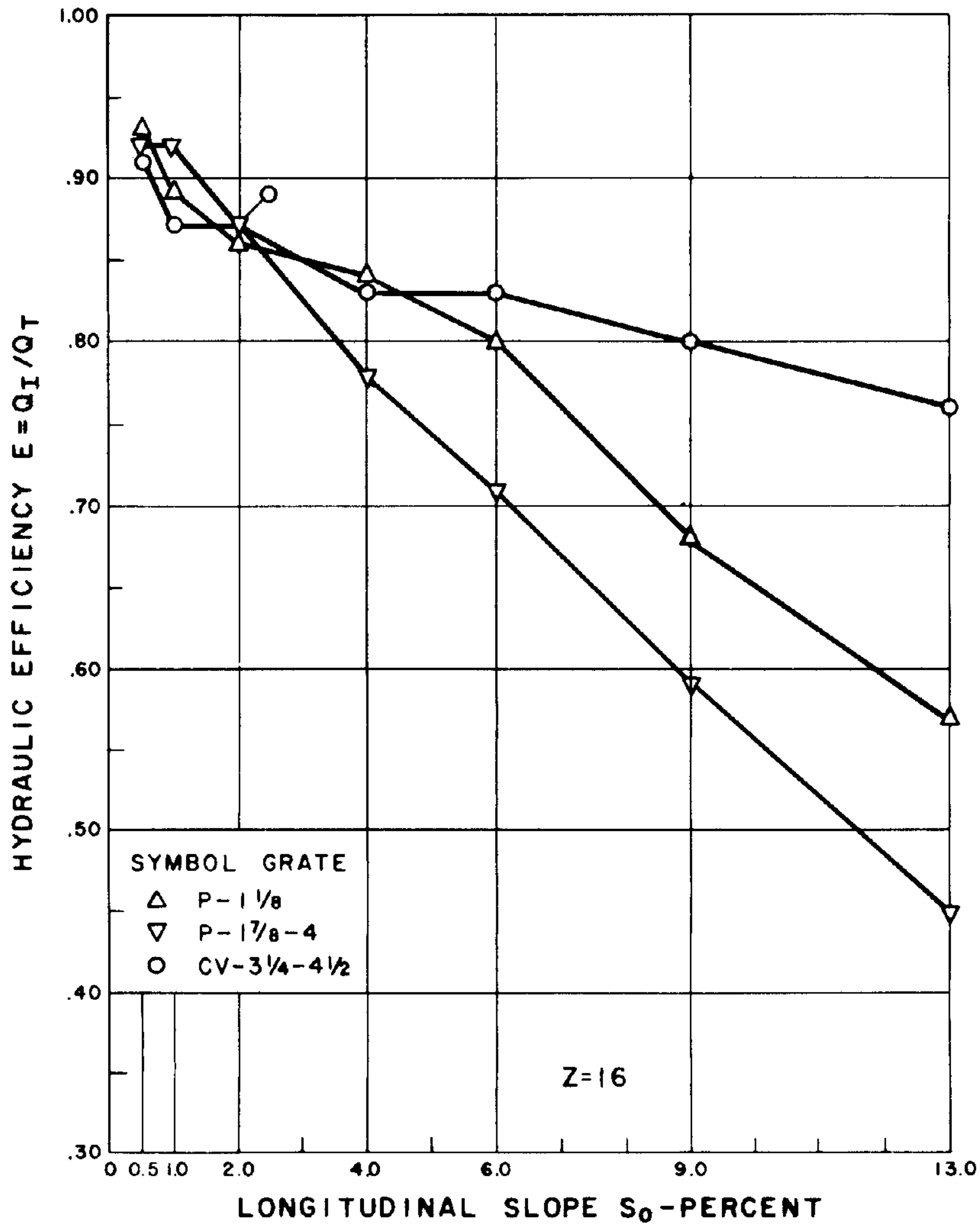


Figure 5-33. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 4.5 ft (1.37 m), Z = 16, 2.0 ft by 2.0 ft (0.61 m by 0.61 m) grates.

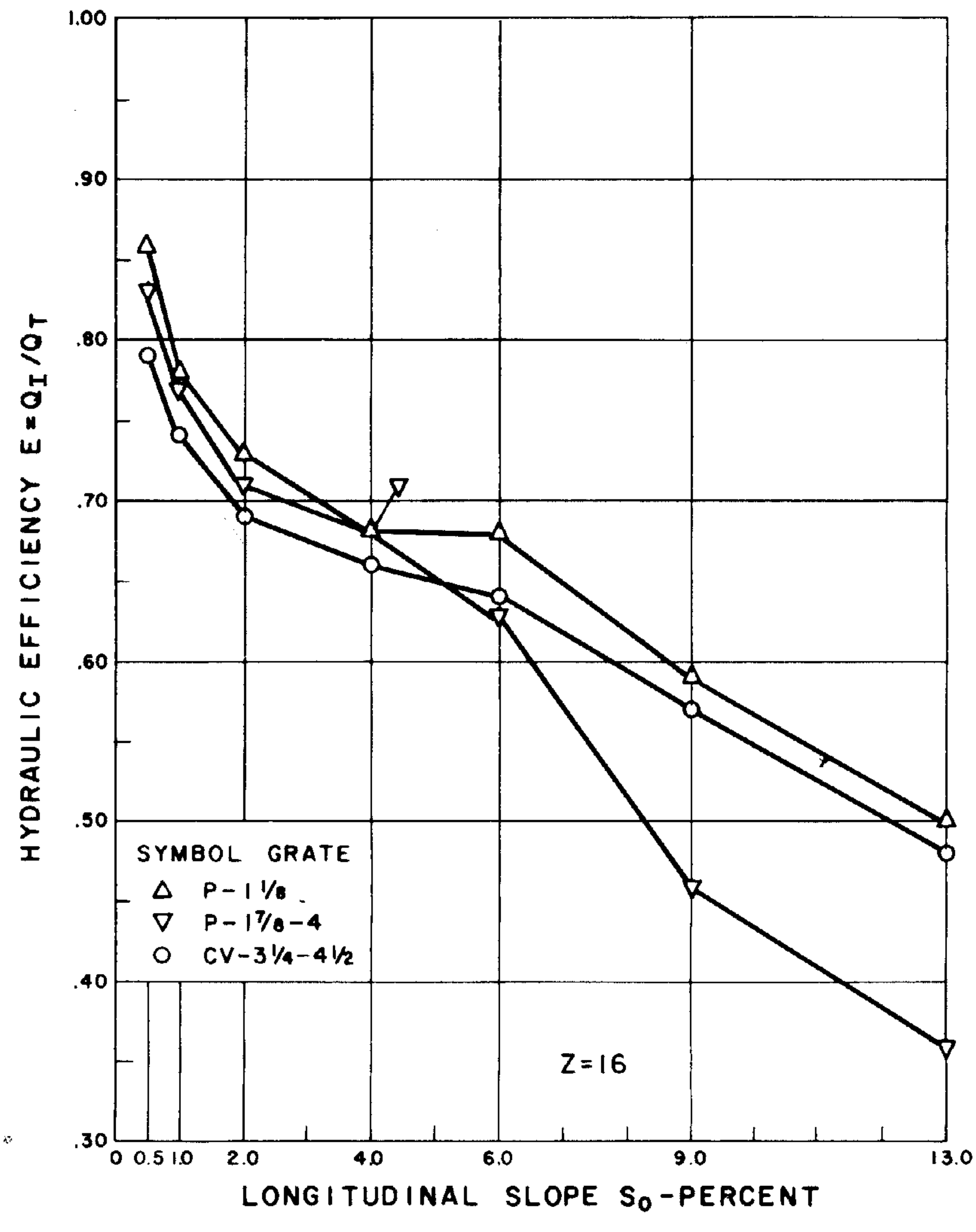


Figure 5-34. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 4.5 ft (1.37 m), Z = 16, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) grates.

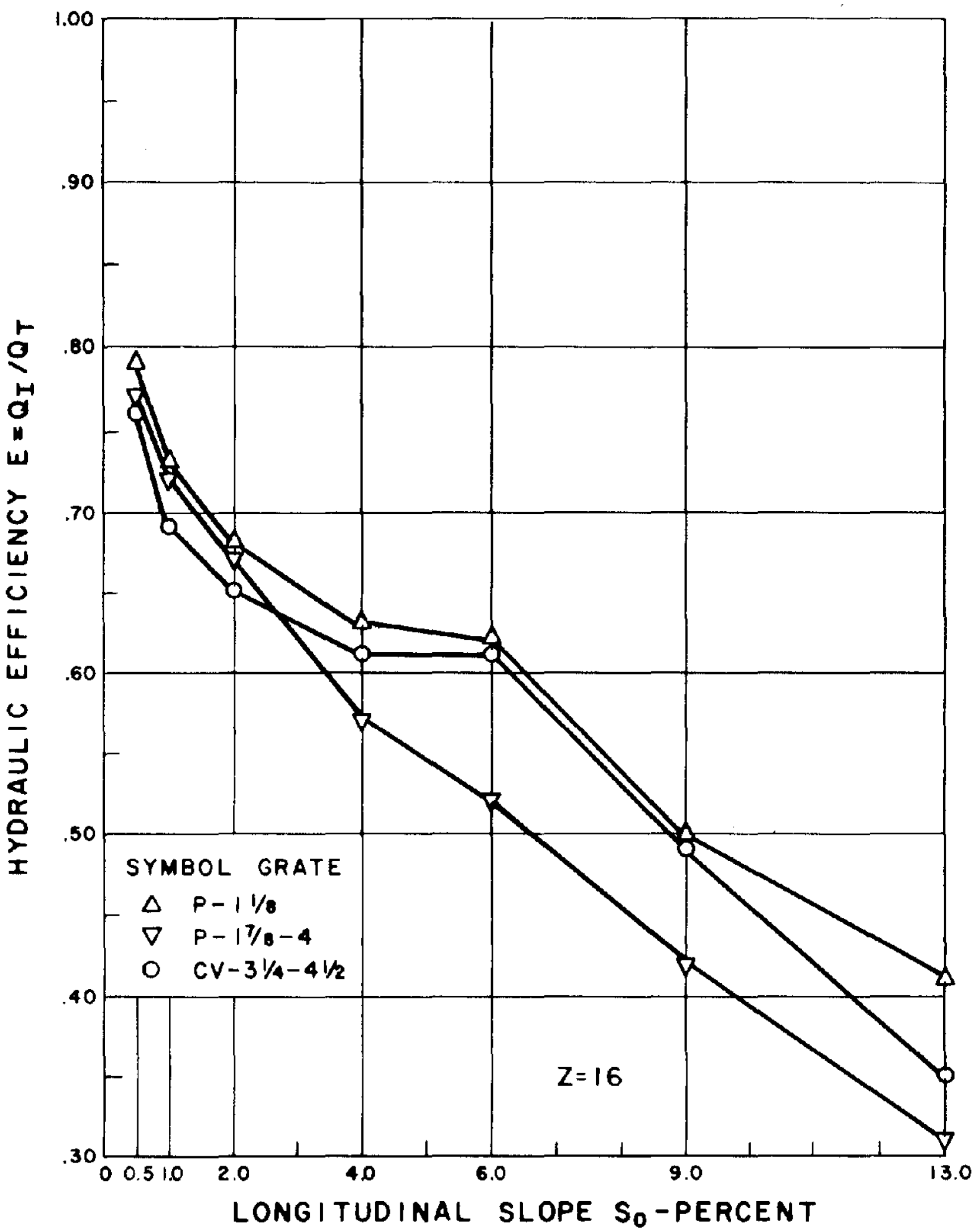


Figure 5-35. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 4.5 ft (1.37 m), Z = 16, 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grates.

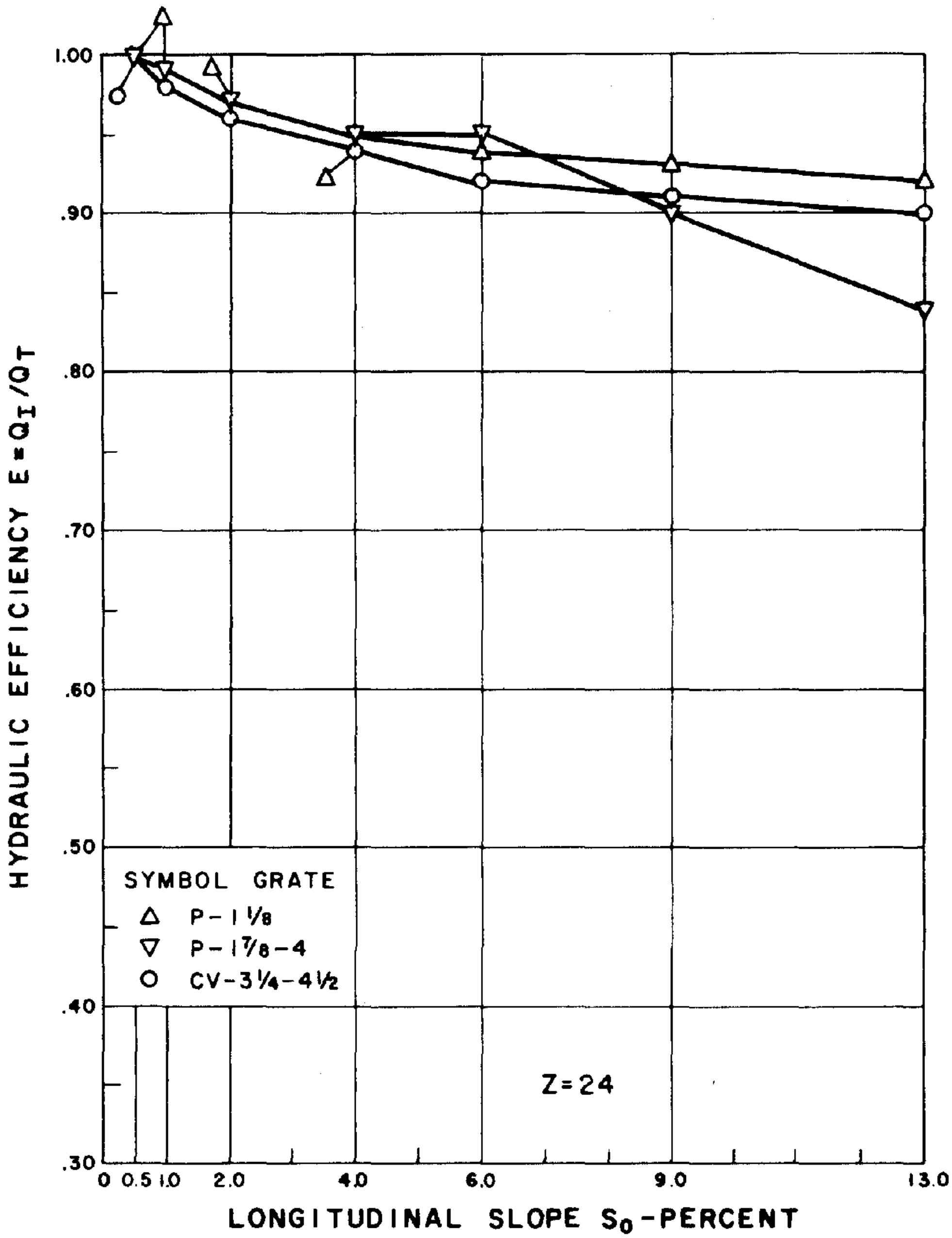


Figure 5-36. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 5.5 ft (1.68 m), Z = 24, 3.0 ft by 4.0 ft (0.91 m by 1.22 m) grates.

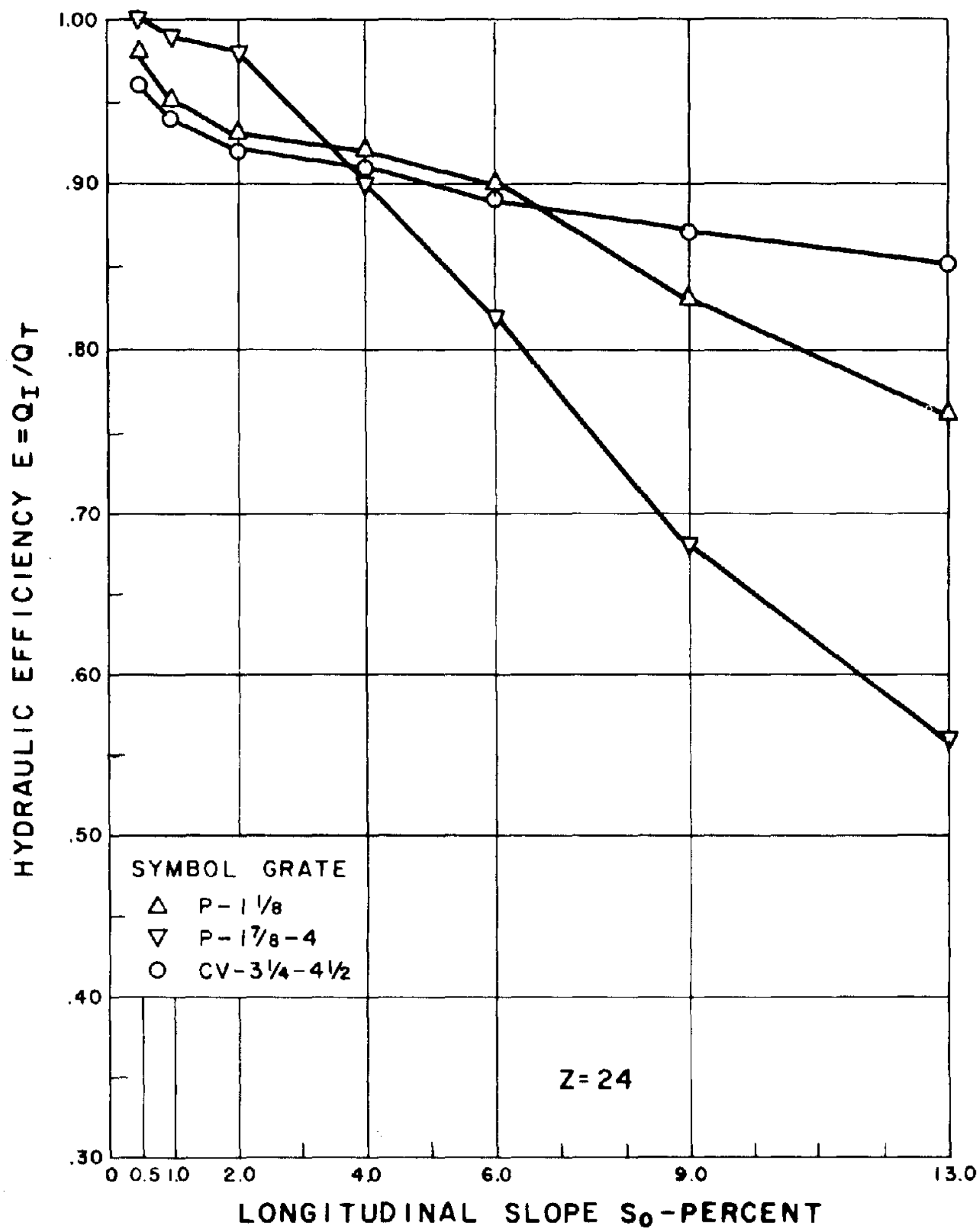


Figure 5-37. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 5.5 ft (1.68 m), Z = 24, 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates.

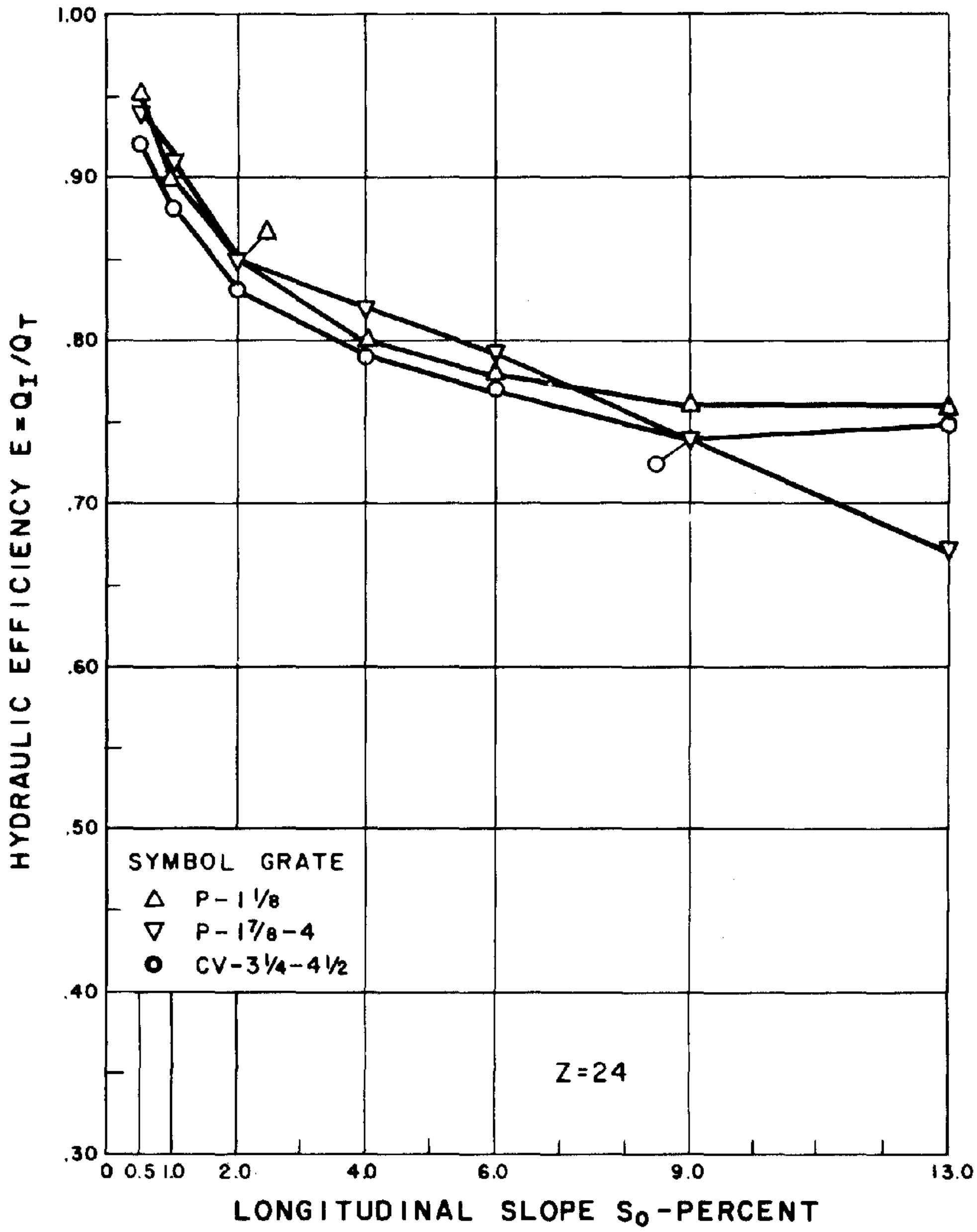


Figure 5-38. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 5.5 ft (1.68 m), Z = 24, 2.0 ft by 4.0 ft (0.61 m by 1.22 m) grates.

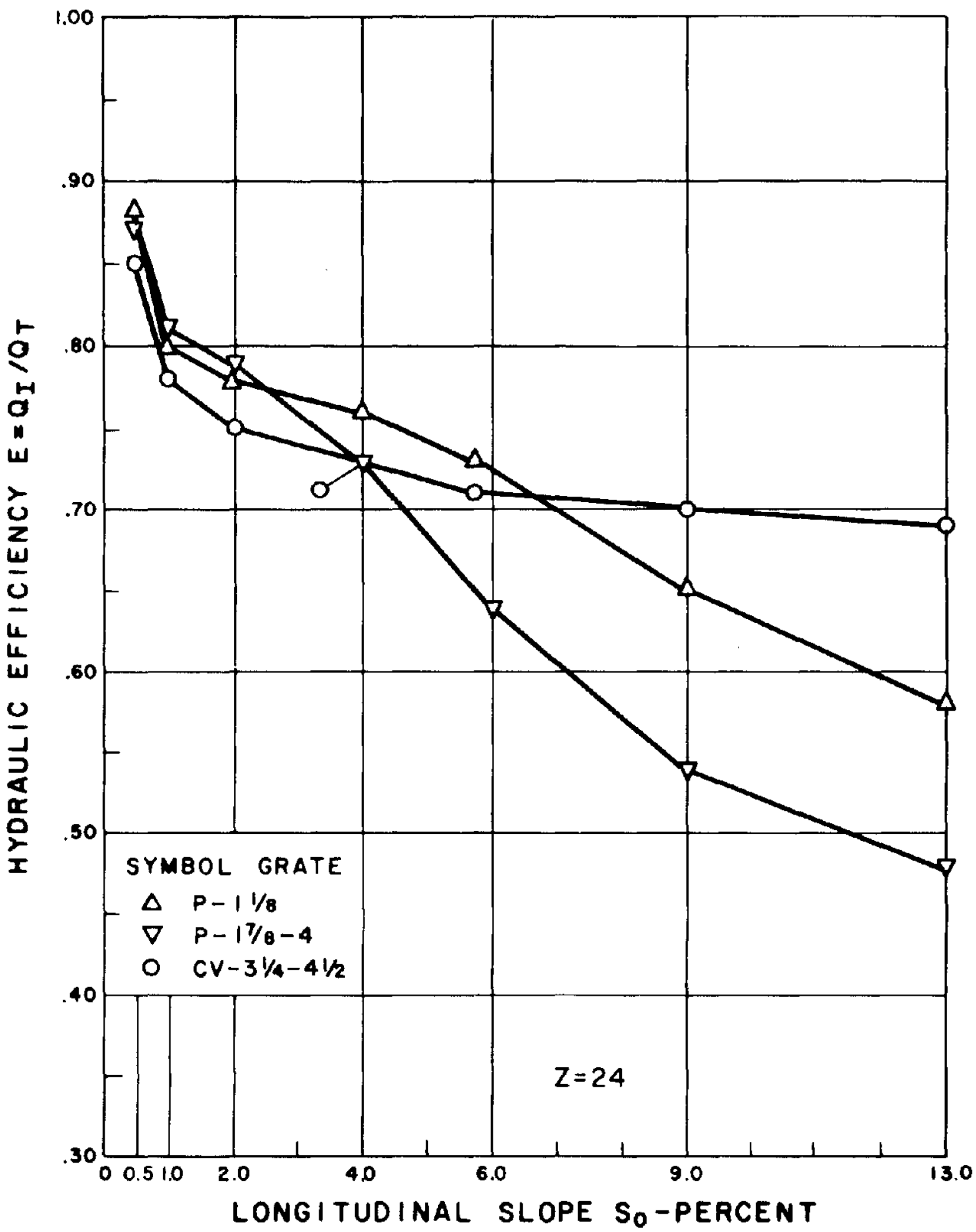


Figure 5-39. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 5.5 ft (1.68 m), Z = 24, 2.0 ft by 2.0 ft (0.61 m by 0.61 m) grates.

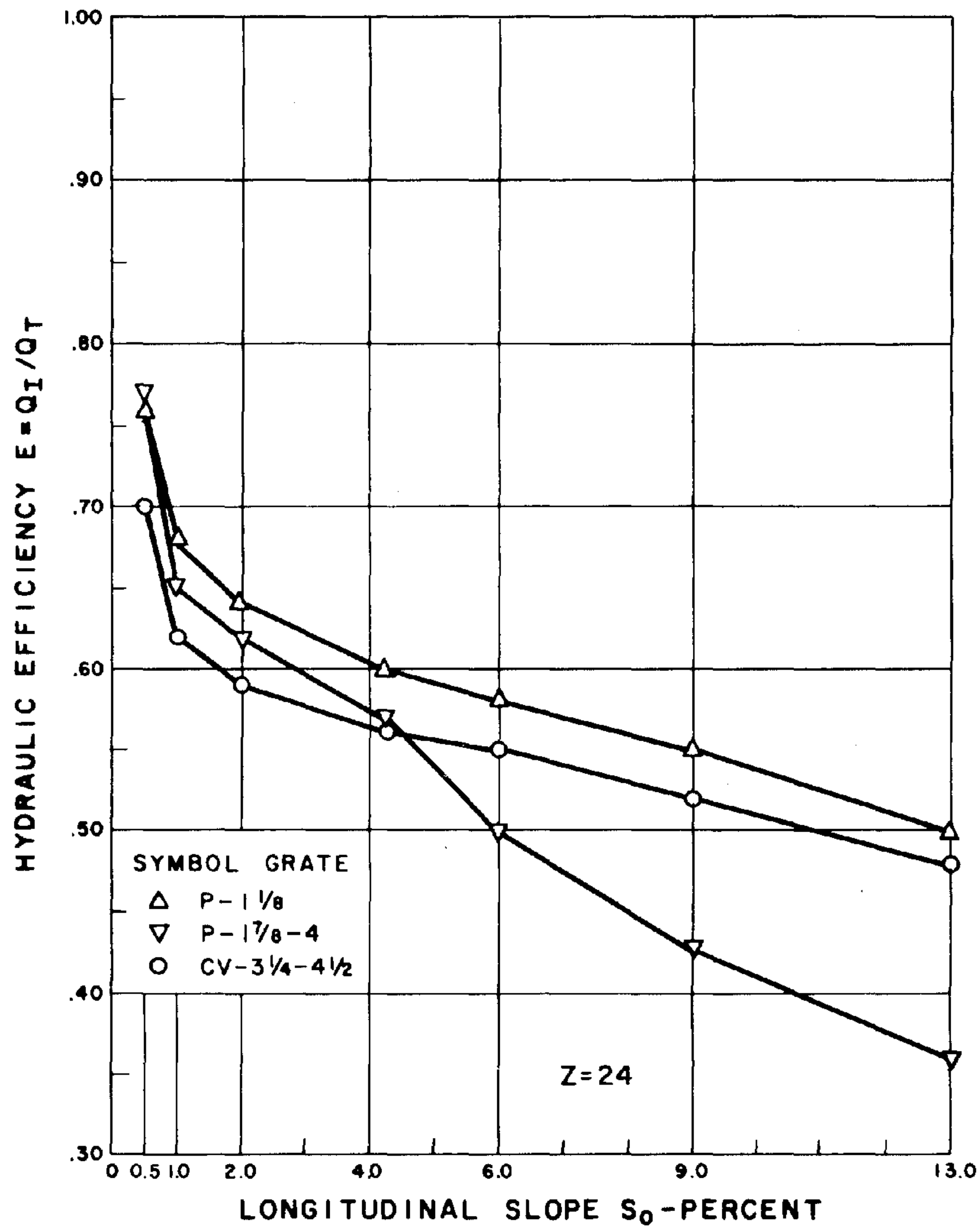


Figure 5-40. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 5.5 ft (1.68 m), Z = 24, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) grates.

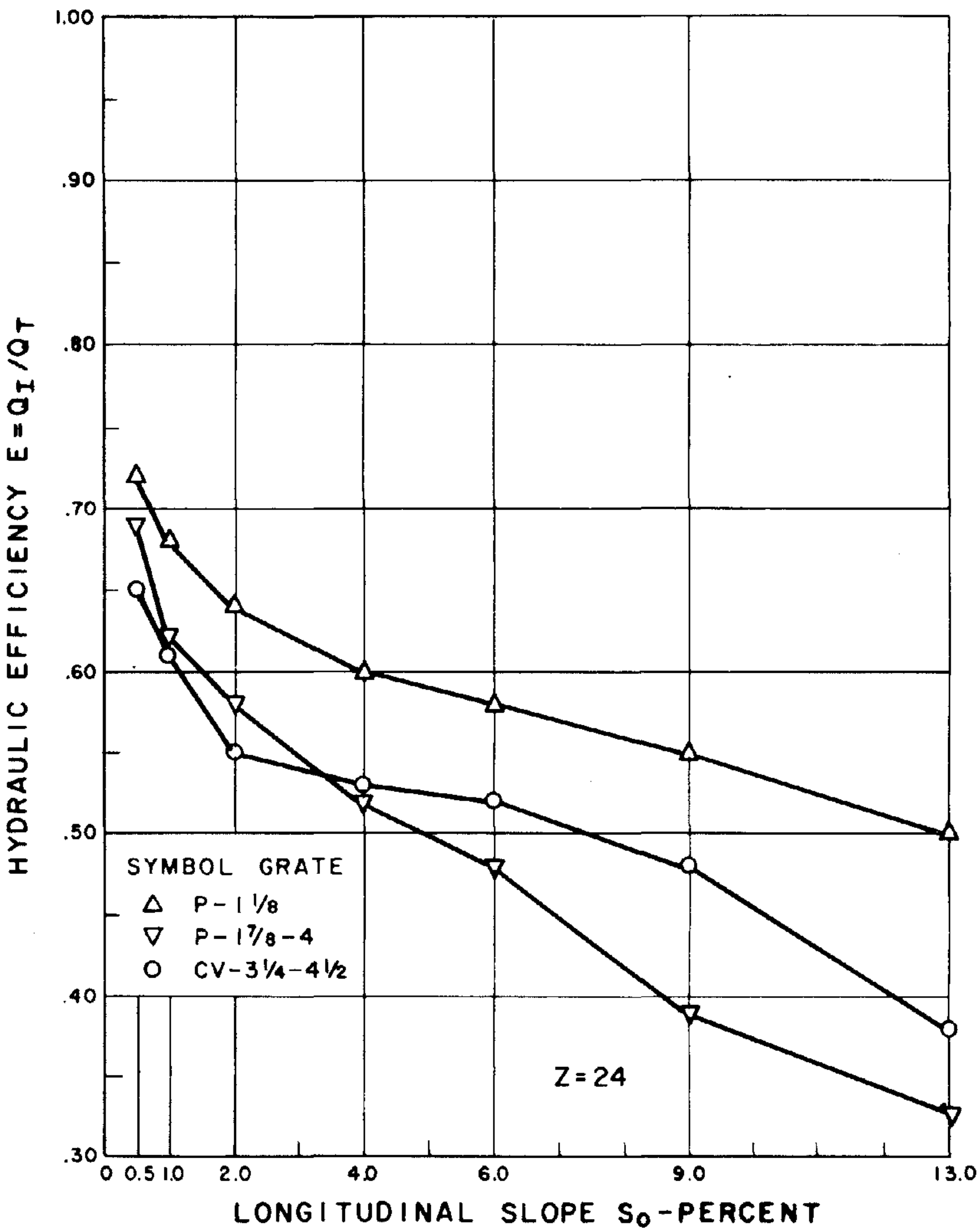


Figure 5-41. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 5.5 ft (1.68 m), Z = 24, 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grates.

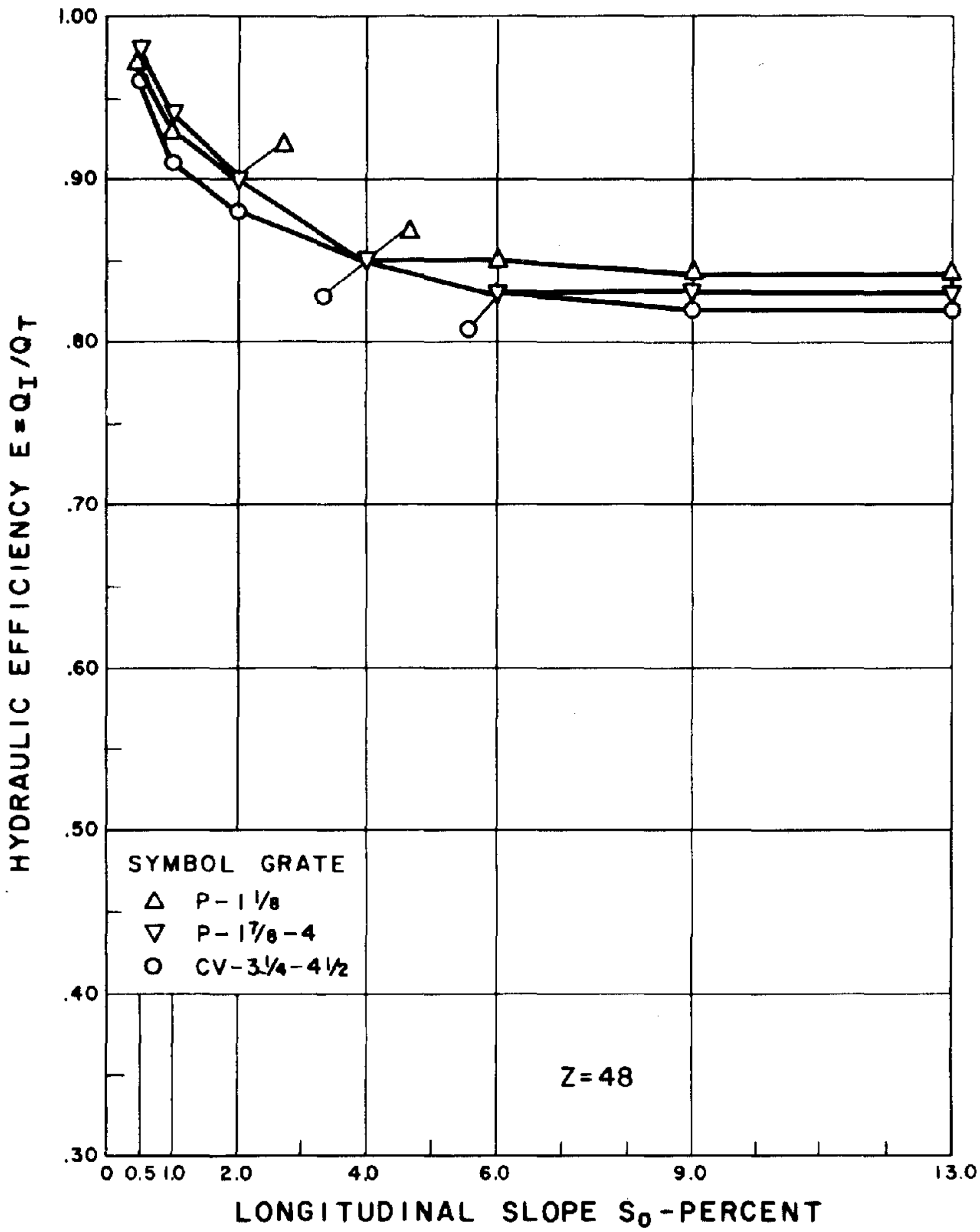


Figure 5-42. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 7.0 ft (2.13 m), Z = 48, 3.0 ft by 4.0 ft (0.91 m by 1.22 m) grates.

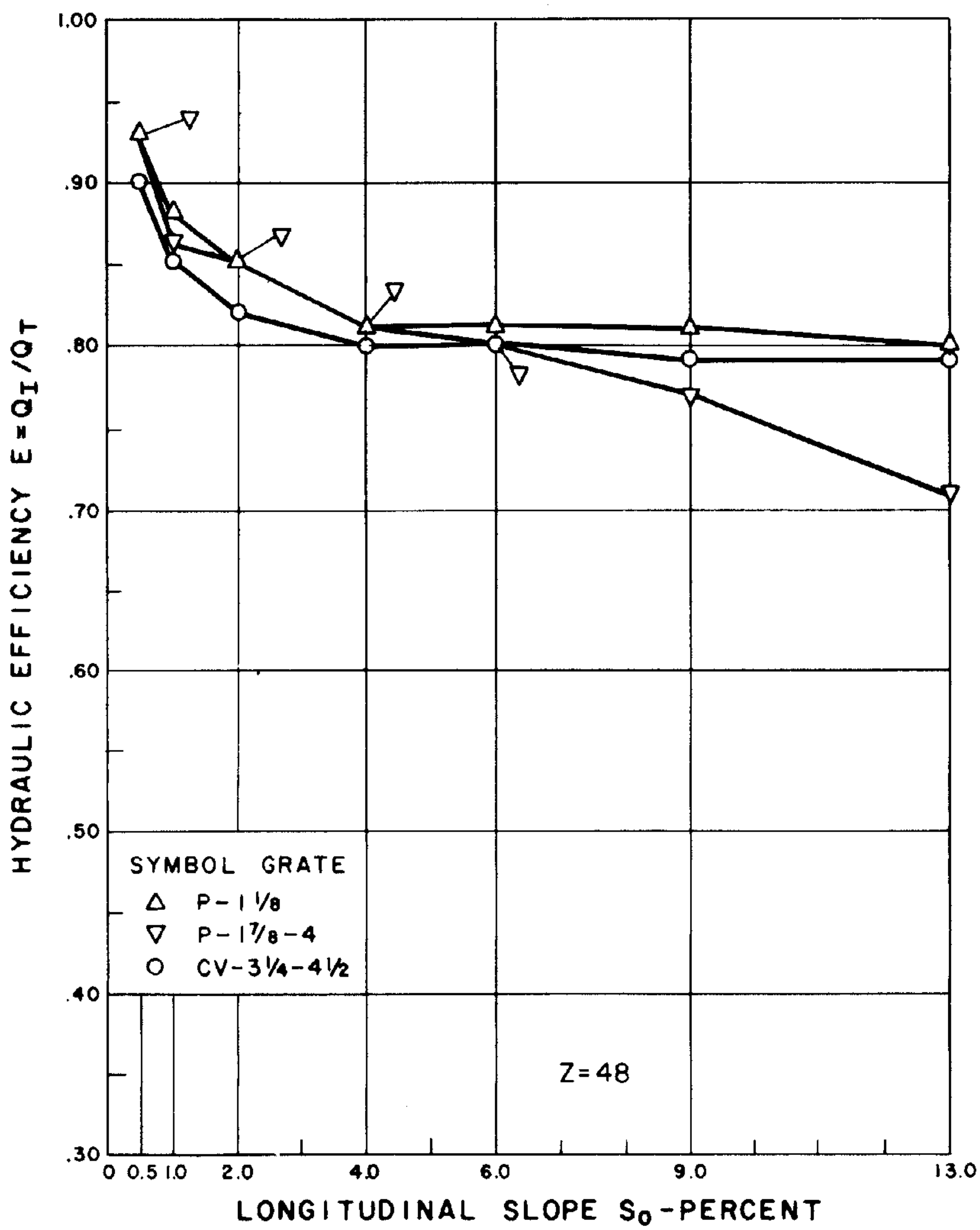


Figure 5-43. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 7.0 ft (2.13 m), Z = 48, 3.0 ft by 2.0 ft (0.91 m by 0.61 m) grates.

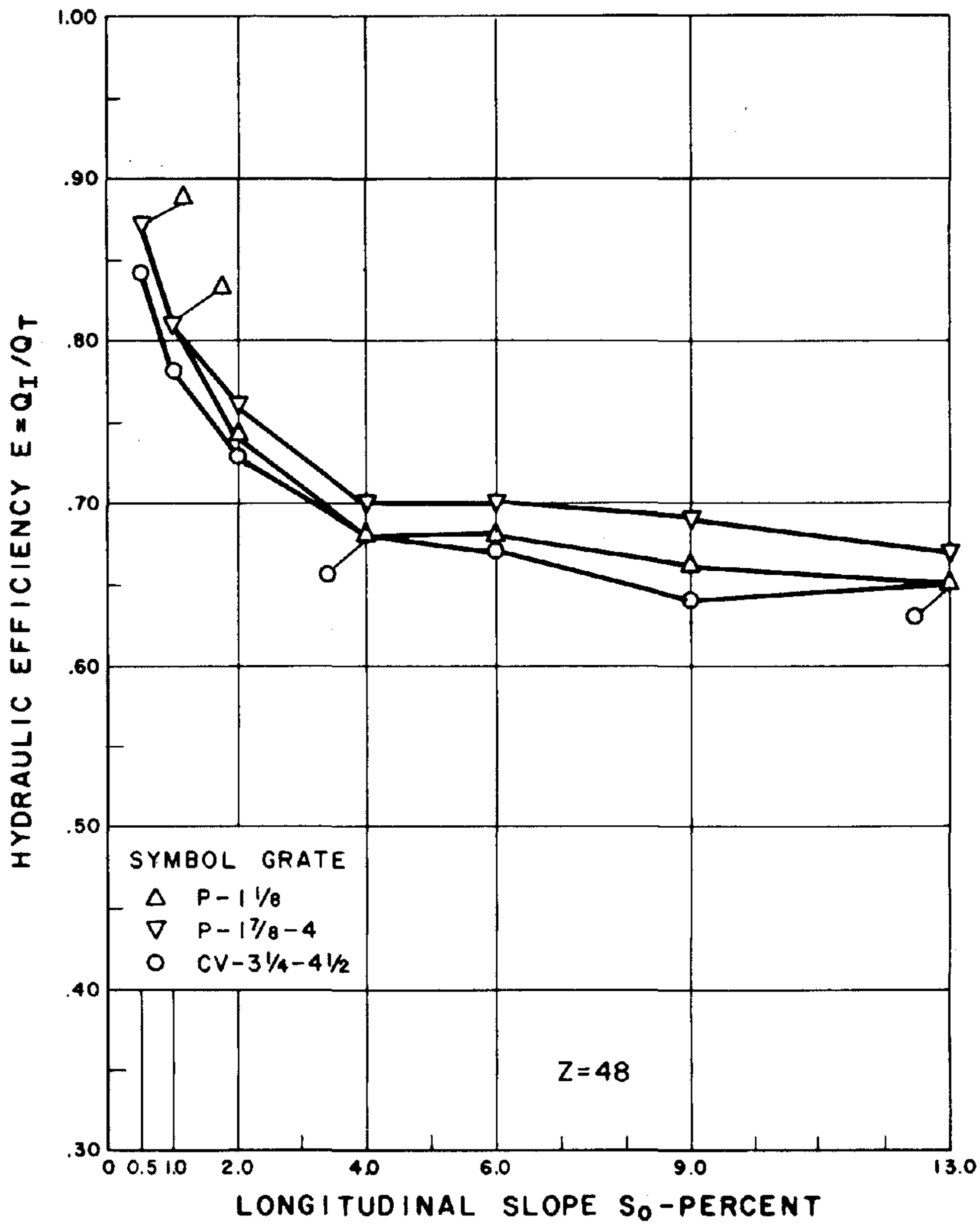


Figure 5-44. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 7.0 ft (2.13 m), Z = 48, 2.0 ft by 4.0 ft (0.61 m by 1.22 m) grates.

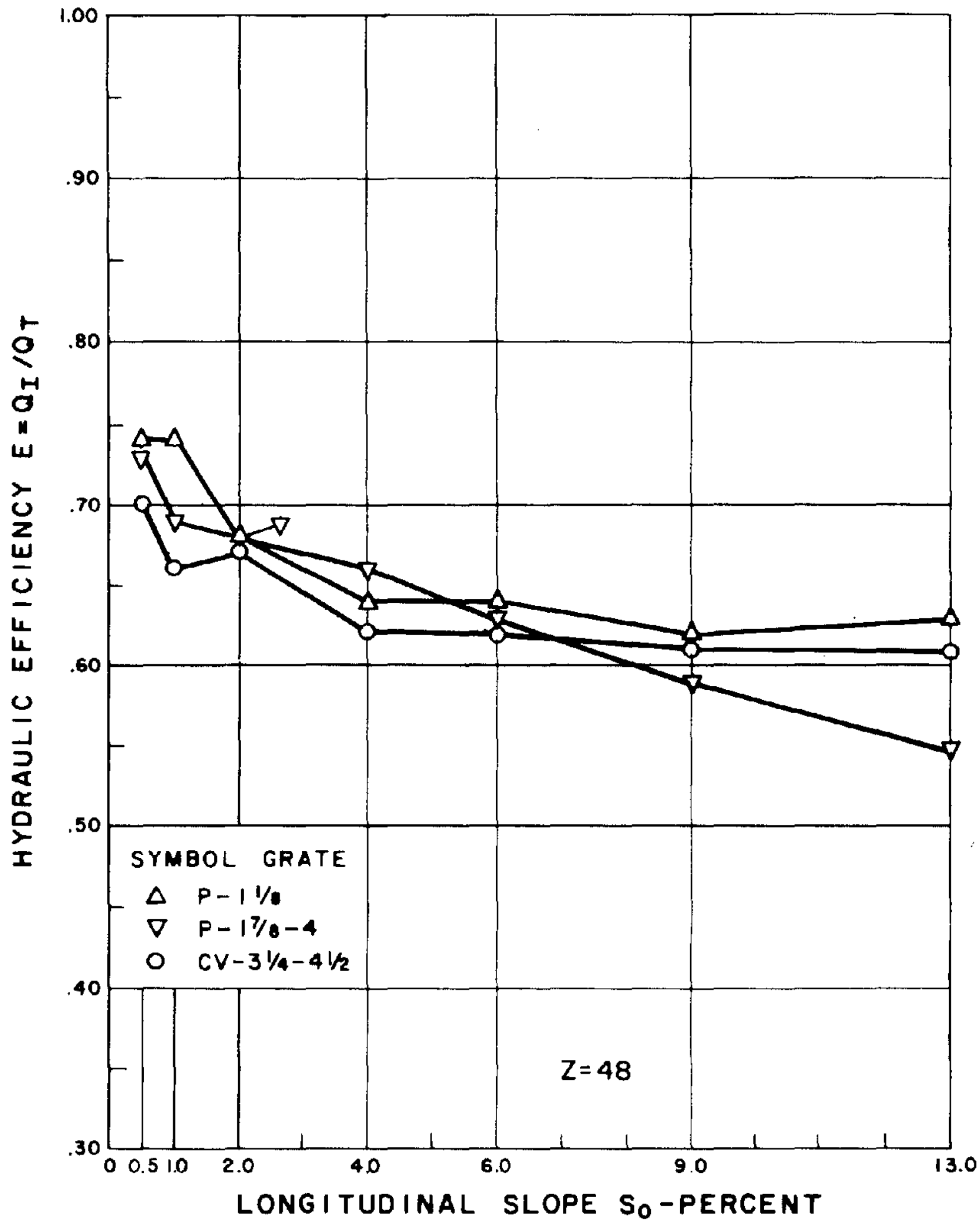


Figure 5-45. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 7.0 ft (2.13 m), Z = 48, 2.0 ft by 2.0 ft (0.61 m by 0.61 m) grates.

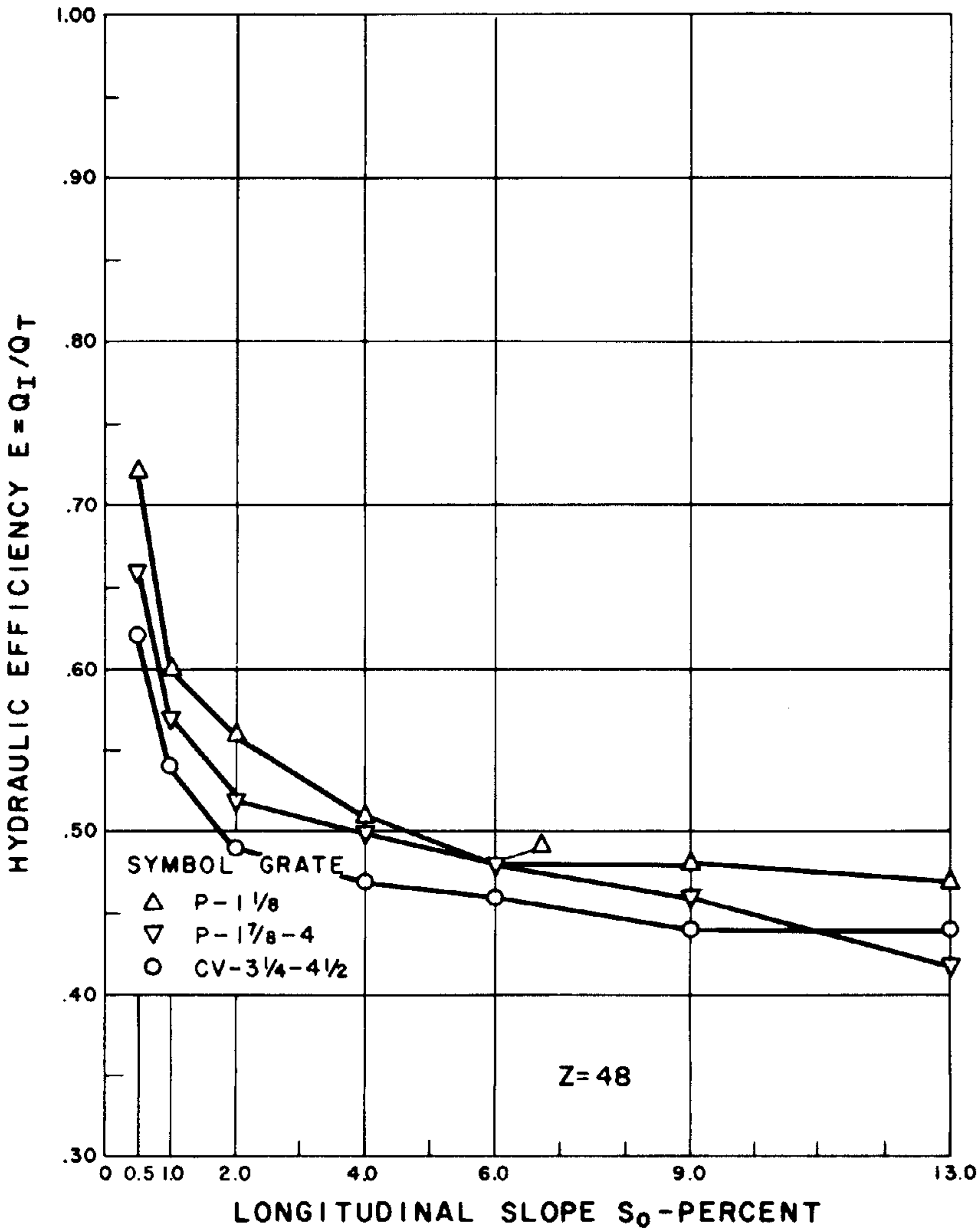


Figure 5-46. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 7.0 ft (2.13 m), Z = 48, 1.25 ft by 2.67 ft (0.38 m by 0.81 m) grates.

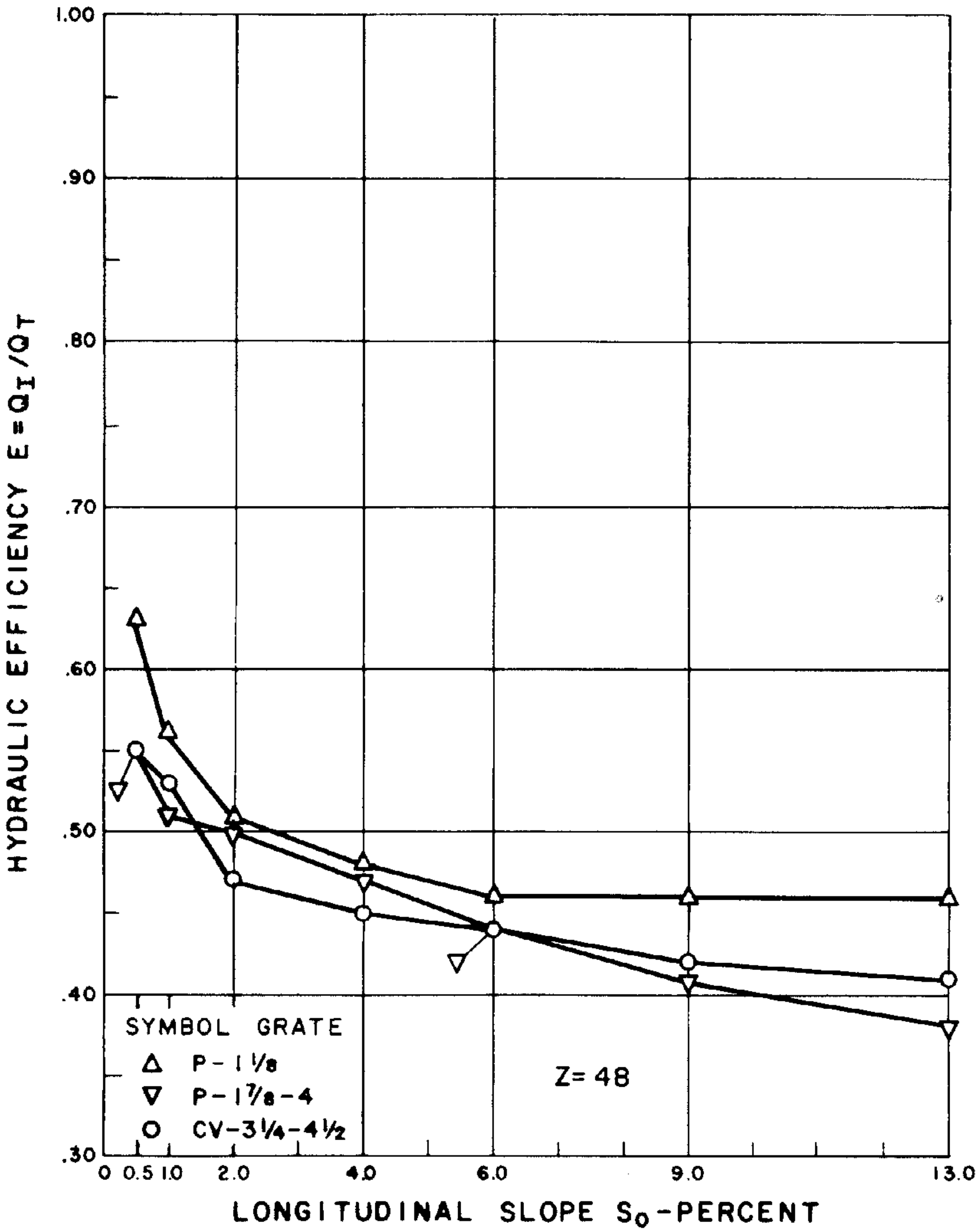


Figure 5-47. - Hydraulic efficiency vs. longitudinal slope for a constant width of spread, T' = 7.0 ft (2.13 m), Z = 48, 1.25 ft by 2.0 ft (0.38 m by 0.61 m) grates.

efficient than the P - 1-7/8 - 4. For low energy gutter flow conditions, the CV - 3-1/4 - 4-1/4 grate inlet is normally somewhat less efficient than the fabricated steel grates.

For a given grate inlet surface area an incremental increase in grate width results in a greater percentage increase in hydraulic efficiency, E, than an incremental increase in length. This was true for all three grate inlet designs.

Recommendations related to specific grate inlet designs were presented in chapter 14 of volume 1 and are repeated here.

1. Relocate the cast spacers used in the parallel bar with transverse spacers (P - 1-1/8) to set flush with the ends of the grate as compared to the 11/16 in (17 mm) offset used in the tested grates (figure 2-1).

2. Roughen the surface of longitudinal bearing bars used in fabricated steel grates when the bar thickness exceeds 1/4 in (6.4 mm). This will help alleviate bicycle tire slippage when the grate is wet.

3. Improve the design of the curved vane grates by placing a radius, possibly 1/4 in (6.4 mm), on the inside surface corners of the end and side members of the grate.