HYDRAULIC AND SAFETY CHARACTERISTICS OF SELECTED GRATE INLETS

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NOTATION

E = hydraulic efficiency

L = length of grate

n = Manning's coefficient of roughness

Q_I = flow intercepted by grate

Q_T = gutter flow

S_o = 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

ABSTRACT

The major objective of the study was to identify, develop, and analyze selected grate inlets which maximize hydraulic efficiency and bicycle safety.

Five hundred and forty bicycle safety tests were conducted on 11 grate inlets using an abandoned roadway 6.7 m (20 ft) wide and 152 m (500 ft) long.

Comprehensive hydraulic and debris tests were conducted on eight grate designs with sizes of 0.61 by 1.22 m (2 by 4 ft) and 0.61 by 0.61 m (2 by 2 ft). Four of the grates that rated highest in the safety tests were selected for hydraulic tests. Three other grate inlet designs with bar spacings similar to grate inlets proven safe were also selected for hydraulic tests. A parallel bar grate was included in the hydraulic test program as a standard with which to compare the performance of the other test grates.

The grate inlets were tested at cross slopes of 1:48, 1:24, and 1:16 and longitudinal slopes of 0.5, 1, 2, 4, 6, 9, and 13 percent, with gutter flows up to 0.16 m^3/s (5.6 ft^3/s). Debris tests were conducted for each grate inlet design and size using 76- by 102-mm (3- by 4-in) Kraft paper. A grate's ability to handle debris without clogging was shown to be most dependent on the spacing of its longitudinal bars.

Test results identified two grate inlets as being slightly less efficient than the parallel bar grate and considerably more efficient than the other grate inlets tested. These two grates are a closely spaced parallel bar grate and a cast grate using "curved vane" transverse bars. A third grate, a parallel bar grate with transverse rods at the surface performed well at longitudinal slopes up to 6 percent.

Introduction

With the recent increase in the number of bicycles on our nation's highways and streets, there has been a corresponding increase in the number of bicycle accidents. Some of these accidents are related to highway grate inlets. The purpose of the comprehensive study reported in this paper was to identify, develop, and analyze selected grate inlets which maximize hydraulic efficiency and bicycle safety.

Fifteen grate inlet designs were initially selected for consideration. They included seven steel-fabricated grates and eight cast grates which can be identified in six categories:

1. Parallel bars grates (two-bar spacings tested)
2. Parallel bar with transverse rod grates (four rod spacings tested for bicycle safety)

3. Reticuline grate

4. 45° tilt bar grates

5. 30° tilt bar grates

6. Curved vane grate

A test program was conducted using two test facilities. The bicycle safety tests were run on an outdoor test site consisting of a 6.7-m (22-ft) wide, 152-m (500-ft) long abandoned roadway. A 2.44-m (8-ft) wide, 18.3-m (60-ft) long hydraulic test flume was constructed in the United States Bureau of Reclamation Hydraulic Research Laboratory and used as a test facility for the hydraulic efficiency tests.

Analysis of Structural Integrity

A general purpose computer program, STR5, was used to perform the structural analysis of the selected grates. The STR5 program has the capability to analyze a wide variety of indeterminate structures from simple planar frames to complex three-dimensional structures. In some cases it was determined by a preliminary STR5 analysis that the bearing bars of the grate acted independently as simple-supported beams. In those cases, a simple beam analysis was performed.

The structural analysis for the grate designs was based on the requirements stated in "Standard Specifications for Highway Bridges," American Association of State Highway and Transportation Officials - AASHTO [1]. The grates were analyzed for a 35.6-kN (8,000-lb) tire load (HS-20-44) with a 30 percent impact factor. The load was theoretically applied to the grate with a 228- by 228-mm (9- by 9-in) contact area as recommended by Ballinger [2].

The grates tested have been code-named to standardize the names. The first symbol refers to the grate design (parallel bar grate - P, curved vane grate - CV, 45° or 30° tilt bar grate - 45 or - 30, and reticuline - R). The second # is the nominal center-to-center longitudinal bar spacing in inches. The last # is the nominal center-to-center transverse bar spacing in inches. Therefore, the P-1-7/8-4 grate refers to a parallel bar grate with center-to-center spacing of the longitudinal bars of 48 mm (1-7/8 in) and center-to-center spacing of the transverse bars of 102 mm (4 in). Figure 1 illustrates the five basic grate inlet designs that were structurally analyzed. The reticuline grate was not structurally analyzed since it is commercially available and the manufacturer's publications provide vehicular load tables based on AASHTO Specifications.

Analysis of Bicycle and Pedestrian Safety

Bicycle and pedestrian safety tests were performed on 11 grate inlets to preselect safe grate inlets for the hydraulic testing phase of the study.

The grate size of 0.61 by 1.22 m (2 by 4 ft) was selected for use in the bicycle safety tests. Table 1 presents principle features of grates evaluated in the test program.

Bicycle safety tests were conducted on a 6.7-m (22-ft) wide paved asphalt road with an average grade of 2 percent. The grates were placed in a concrete vault which held them level and flush with the road surface. A 200-mm (7.9-in) high concrete curb was provided along the approach to the grate for the uphill and downhill straight runs. The curb was removed for turning tests.

Seven adults and four children served as bicyclists. A total of 174 uphill, 164 downhill, and 201 turning runs were made during the safety test program. Speeds ranged from 37 to 8.0 km/h (23 to 5 m/h). Grates were kept wet for all test runs.

Three common types of bicycles were used for the tests: a 686-mm (27-in) ten-speed, a 660-mm (26-in) three-speed, and a 508-mm (20-in) highrise. Both "clincher" and "sew-up" tires were used on the ten-speed and "slick" and "knobby" balloon tires were used on the highrise bicycle. Tire widths ranged from 22 mm (7/8 in) to 56 mm (2-3/16 in).

Data collected included measurements by a team of observers, bicyclists' perceptions, and several types of video records. The evaluation of grates in relation to pedestrian safety was based upon inspection of grates in relation to foot sizes and shoe types.

The transverse spacing of grate bars is a critical factor in bicycle safety performance. It is a more critical factor than whether the grate is of the reticuline, 45° tilt bar, curved vane, or parallel bar with transverse rod type. The analyses suggest that deterioration in bicycle safety performance begins as transverse spacings are increased somewhat above 102 mm (4 in). Significant skidding occurred on virtually all grates as a result of turning runs as illustrated in figure 2. Keeping the grates wet increased the chances for skidding.

The grates which proved the least satisfactory on bicycle safety tests were also those which appeared least satisfactory from a pedestrian standpoint. Table 2 lists the final ranking of the grates for bicycle-pedestrian safety.

Of the 11 grates tested, 7 showed markedly superior performance over the remaining 4. Of the seven in the high-performance group, four were of the 45° tilt-bar type with transverse bar spacing at or less than 102 mm (4 in). Two were of the parallel bar with transverse rod type with transverse bar spacings of 102 mm (4 in). The reticuline grate type completed the high performance group.

Two grates were tested in the hydraulic efficiency tests which were not tested in the bicycle safety tests. The curved vane grate (CV-3-1/4-4-1/4) design was very similar to the 45-3-1/4-4 grate which satisfactorily passed the bicycle safety tests. The parallel bar grate with transverse spacers (P-1-1/8) was tested independently for bicycle safety [3].

Test Facility and Experimental Approach

To accurately investigate the hydraulic characteristics of grate inlets, the decision was made to use a full-scale test facility. The width of the roadbed selected for the test facility was 2.4 m (8 ft) including a 0.61-m (2-ft) gutter section and one-half of a 3.7-m (12-ft) traffic lane, generally considered the allowable width of flow spread. The test roadbed was 18.3 m (60 ft) long with the grate inlet test section located 12.2 m (40 ft) from the headbox. The facility was designed and constructed to accommodate the following test conditions:

Longitudinal slopes, S_o	- 0.5 to 13 percent
Cross slopes, $1/Z$	- 1:48 to 1:16
Maximum gutter flow, Q_T	- 0.16 m^3/s (5.6 ft^3/s)
Manning roughness factor	- $n = 0.016$ to 0.017

To complete the 1,800 hydraulic tests in a reasonable amount of time, consideration was given to designing a hydraulic test facility which emphasized simplicity and ease of operation. Figures 3 and 4 are schematic drawings of the test facility.

For each grate design, size, longitudinal slope, and cross slope, five different gutter flows were tested. The maximum gutter flow was limited by either the pump capacity of 0.16 m^3/s (5.6 ft^3/s) or width of spread limited to $T' = 2.3$ m (7.5 ft). The minimum gutter flow was that flow which was completely captured by the grate inlet or provided a flow spread of $T' = 0.61$ m (2 ft). The five data points obtained were sufficient to develop curves relating hydraulic efficiency, E = intercepted gutter flow/total gutter flow, $E = Q_I/Q_T$, to gutter flow, Q_T and width of spread, T', for each combination of longitudinal and cross slopes. Inlet capacity curves relating longitudinal slope, S_o, cross slope, $1/Z$, gutter flow, Q_T, intercepted flow, Q_I, width of spread, T, and hydraulic efficiency, E, were developed from the previously mentioned curves. Figure 5 shows a typical inlet capacity curve complete with data points.

With a selected gutter flow and longitudinal slope, a designer can determine the intercepted flow, Q_I, and width of spread, T, for a given size of grate and highway cross slope, $1/Z$.

Discussion of Test Results

The preliminary structural analysis and bicycle-pedestrian analysis led to the selection of eight grate designs for the hydraulic tests. They included a steel-fabricated parallel bar grate (P-1-7/8) which was not bicycle safe but which provided an excellent standard for hydraulic efficiency with which to compare other grate inlet designs. Three other steel-fabricated grates were also tested - parallel bar grate with transverse rods at the surface (P-1-7/8-4), parallel bar grate with spacers (P-1-1/8), and a reticuline grate (R). Four cast grates were tested. They included two 45° tilt bar grates (45-3-1/4-4, 45-2-1/4-4), a 30° tilt bar grate (30-3-1/4-4), and a curved vane grate (CV-3-1/4-4-1/4) design. Figure 1 illustrates schematic drawings of the steel-fabricated and cast grates.

The test results are covered in detail in FHWA-RD-77-24, entitled, "Bicycle Safe Grate Inlets Study" [4]. The flow into and around each of the eight grate inlets is similar in many respects to an open hole. The flow conditions are determined by the longitudinal slope, cross slope, and gutter flow.

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 steeper longitudinal slopes, the same gutter flow occupies a smaller cross-sectional area and, therefore, a greater percentage of the flow passes over the grate inlet. If no flow splashes completely across the grate, intercepted flow is greater and, hence, hydraulic efficiency is higher. All of the grate inlets, except the parallel bar and the curved vane grate, had splashing occurring under some flow conditions. The other six grates show a decrease in hydraulic efficiency above a limiting longitudinal slope, related to grate design, size, and cross slope as shown in table 3.

The seven bicycle-safe grate designs (discounting the parallel bar grate) can be classified in three hydraulic efficiency performance groups at the steeper longitudinal and cross slopes. The CV-3-1/4-4-1/4 and P-1-1/8 grates are consistently superior to the other bicycle-safe grates tested. The 0.61- by 1.22-m (2- by 4-ft), CV-3-1/4-4-1/4, and P-1-1/8 grates are within 3 to 4 percent of the parallel bar grate for the same test conditions.

At the other extreme, the reticuline grates generally rank last. At higher gutter flows with steep longitudinal and cross slopes, the reticuline grates usually had the lowest efficiency of the grates tested (for longitudinal slopes less than 3 percent, the reticuline grate is as efficient as the other grates). The remaining grates; the 45°-2-1/4-4, 45°-3-1/4-4, P-1-7/8-4, and the 30°-3-1/4-4 tend to have hydraulic efficiencies very close to each other. They rank somewhat better than the reticuline grates, but far below the CV-3-1/4-4-1/4 and P-1-1/8 grates.

Table 4 shows the rank and hydraulic efficiency of each grate size and design for Z = 24 and 16 at a longitudinal slope of 9 percent with Q_T = 0.14 m^3/s (4.9 ft^3/s).

Figures 6 through 8 show the hydraulic efficiency performance of the eight 0.61- by 1.22-m (2- by 4-ft) grates for a constant width of spread, T', as the longitudinal slope, S_o, varies from 0.5 to 13 percent. Each figure represents a different cross slope setting. Similar performance curves can be generated for the eight 0.61- by 0.61-m (2- by 2-ft) grates. The figures are useful for comparing hydraulic efficiencies of the test grates for various longitudinal slopes. The steel-fabricated grates which are larger in effective port area than the cast grates, look superior up to the point where flow rates and velocities are great enough to make the grate design the most important factor.

The parallel bar grate (P-1-7/8) is consistently first, followed by the CV-3-1/4-4-1/4 and the P-1-1/8. Except for low longitudinal slopes, the reticuline grates are generally the least efficient grates tested. The remaining four grates change order, but basically make up the middle performance group.

Table 5 shows the ranking of the various grate designs based on the debris tests. The table shows the debris handling advantage for grates with the 83-mm (3-1/4-in) longitudinal bar spacing over those with smaller longitudinal bar spacings.

Summary and Conclusions

In applying the three major test criteria for grate inlets, hydraulic efficiency, safety, and debris handling ability, it is clear that the safety and debris handling characteristics of a grate inlet are not as dependent on longitudinal slope, S_o, as the hydraulic characteristics. The hydraulic test results indicate that above certain longitudinal slopes, S_o, the hydraulic efficiency, E, of several grate inlets is adversely affected by the high velocity flow striking the transverse bar members and splashing over the inlet The specific longitudinal slopes depend on such variables as cross slope, 1/Z, gutter flow, Q_T, and grate length, L, but can be identified in two generalized categories as favorable and unfavorable gutter flow conditions.

Results of the debris tests indicate that the wider the longitudinal bar spacing, the better the debris handling ability of a grate inlet.

The bicycle safety tests suggest that the deterioration in bicycle safety performance begins as transverse bar spacing is increased above 102 mm (4 in). In addition, grates having large, nearly square openings, 83 by 102 mm (3-1/4 in by 4 in) are also judged to pose some potential danger to pedestrians.

Table 6 is a summary presentation of the test results for debris, safety, and hydraulic efficiency considerations. An attempt has been made to classify the selected grates into high and low performance groups for the three major areas of consideration. The high performance (class I) grates for bicycle safety are low performers (class II) with respect to debris handling capabilities. For favorable gutter flow conditions (no splashing), the class I grates are slightly more efficient (less than 6 percent) than the class II grates. For the unfavorable gutter flow conditions, hydraulic efficiencies vary as much as 34 percent between class I and class II grates for a 0.61-m (2-ft) grate length and 15 percent for a

1.22-m (4-ft) grate length. The composite selection in the table are the authors' overall classification of the selected grates tested.

ACKNOWLEDGMENTS

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

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[2] Ballinger, C. A., and Gade, R. H., "Evaluation of the Structural Behavior of Typical Highway Inlet Grates, with Recommended Structural Design Criteria," report No. FHWA-RD-73-90, December 1973.

[3] Los Angeles County Flood Control District, "Evaluation of Three Types of Catch Basin Grates for Streets with Bicycle Traffic," Systems and Standards Group, Design Division, January, 1973.

[4] Burgi, P. H., and Gober, D. E., "Bicycle-Safe Grate Inlets Study, Vol. 1, Hydraulic and Safety Characteristics of Selected Grate Inlets on Continuous Grades," report No. FHWA-RD-77-24, June 1977.

Table Titles

Table 1 - *Principal grate dimensions*

(Note: 1 in = 25.4 mm)

Type	Longitudinal spacing* (inches)	Longitudinal bar width (inches)	Transverse spacing** (inches)	Transverse bar width (inches)	Manufacturing process
Reticuline	2-5/8	1/4	***5	3/16	Fabricated steel
Parallel bar	1-7/8	1/4	4	3/8 rod	Fabricated steel
Parallel bar	1-7/8	1/4	6	3/8 rod	Fabricated steel
Parallel bar	1-7/8	1/4	8	3/8 rod	Fabricated steel
Parallel bar	2-3/8	1/4	4	3/8 rod	Fabricated steel
45° tilt-bar	2-1/4	1/2	3	3/4	Cast****
45° tilt-bar	2-1/4	1/2	4	3/4	Cast****
45° tilt-bar	2-1/4	1/2	6-1/4	3/4	Cast****
45° tilt-bar	3-1/4	1/2	3	3/4	Cast****
45° tilt-bar	3-1/4	1/2	4	3/4	Cast****
45° tilt-bar	3-1/4	1/2	6-1/4	3/4	Cast****

* Center-to-center spacing of bars parallel to direction of flow.
** Center-to-center spacing of bars transverse to direction of flow.
*** Center-to-center spacing of rivets - reticuline grate only.
**** Grates used for the tests were made of white oak to simulate cast grates.

Table 2. - *Grate ranking for bicycle safety*

Grate design	Composite rank
45-3-1/4 - 3	1
P-1-7/8 - 4	2
Reticuline	3
45-3-1/4 - 4	4-5
45-2-1/4 - 4	4-5
P-2-3/8 - 4	6
45-2-1/4 - 3	7
P - 1-7/8 - 6	8
45-2-1/4 - 6-1/4	9
45-3-1/4 - 6-1/4	10
P-1-7/8 - 8	11

Table 3. - *Limiting longitudinal slopes*

(1 m = 3.28 ft)

Grate design	Size	Z = 48	Z = 24	Z = 16
P-1-1/8	0.61 by 0.61 m	>13%	9%	6%
	0.61 by 1.22 m	>13%	>13%	10%
45-2-1/4-4	0.61 by 0.61 m	>13%	8%	4%
	0.61 by 1.22 m	>13%	13%	7%
45-3-1/4-4	0.61 by 0.61 m	>13%	7%	6%
	0.61 by 1.22 m	>13%	13%	7%
P-1-7/8-4	0.61 by 0.61 m	13%	6%	2%
	0.61 by 1.22 m	13%	13%	8%
30-3-1/4-4	0.61 by 0.61 m	>13%	7%	4%
	0.61 by 1.22 m	>13%	9%	6%
Reticuline	0.61 by 0.61 m	6%	3%	2%
	0.61 by 1.22 m	13%	6%	3%

Table 4. - *Comparison of test grates at 9 percent longitudinal slope*

Rank	Z = 24				Z = 16			
	2 by 2 ft (0.61 by 0.61 m)		2 by 4 ft (0.61 by 1.22 m)		2 by 2 ft (0.61 by 0.61 m)		2 by 4 ft (0.61 by 1.22 m)	
		E		E		E		E
1	P - 1-7/8	71%	P - 1-7/8	75%	P - 1-7/8	81%	P - 1-7/8	84%
2	CV - 3-1/4 - 4-1/4	68%	P - 1-1/8	72%	CV - 3-1/4 - 4-1/4	78%	CV - 3-1/4 - 4-1/4	82%
3	P - 1-1/8	59%	CV - 3-1/4 - 4-1/4	71%	P - 1-1/8	64%	P - 1-1/8	82%
4	45 - 3-1/4 - 4	49%	P - 1-7/8 - 4	68%	P - 1-7/8 - 4	55%	45 - 2-1/4 - 4	77%
5	45 - 2-1/4 - 4	49%	45 - 3-1/4 - 4	68%	45 - 2-1/4 - 4	54%	45 - 3-1/4 - 4	76%
6	30 - 3-1/4 - 4	48%	45 - 2-1/4 - 4	66%	45 - 3-1/4 - 4	52%	P - 1-7/8 - 4	73%
7	P - 1-7/8 - 4	45%	30 - 3-1/4 - 4	65%	30 - 3-1/4 - 4	51%	30 - 3-1/4 - 4	71%
8	Recticuline	45%	Reticuline	65%	Reticuline	49%	Reticuline	70%

Table 5. - *Average debris handling efficiencies for test grates*

Rank	Grate style	Longitudinal slope	
		.5%	4%
1	CV - 3-1/4 - 4-1/4	46	61
2	30 - 3-1/4 - 4	44	55
3	45 - 3-1/4 - 4	43	48
4	P - 1-7/8	32	32
5	P - 1-7/8 - 4	18	28
6	45 - 2-1/4 - 4	16	23
7	Reticuline	12	16
8	P - 1-1/8	9	20

Table 6. - *Grate inlet classification*

Debris	Safety	Hydraulics		Composite selection	
		Favorable gutter flow conditions	Unfavorable gutter flow conditions	Favorable gutter flow conditions	Unfavorable gutter flow conditions
Class I (high performance)					
CV - 3-1/4 - 4-1/4	P - 1-7/8 - 4	P - 1-7/8 - 4	CV - 3-1/4 - 4-1/4	P - 1-7/8 - 4	CV - 3-1/4 - 4-1/4
30° - 3-1/4 - 4	Reticuline	P - 1-1/8	P - 1-1/8	P - 1-1/8 Reticuline	P - 1-1/8
45° - 3-1/4 - 4	P - 1-1/8*	Reticuline		45° - 3-1/4 - 4	
Class II (low performance)					
P - 1-7/8 - 4	45° - 3-1/4 - 4	CV - 3-1/4 - 4-1/4	45° - 3-1/4 - 4	CV - 3-1/4 - 4-1/4	45° - 3-1/4 - 4
45° - 2-1/4 - 4	45° - 2-1/4 - 4	45° - 3-1/4 - 4	P - 1-7/8 - 4	45° - 2-1/4 - 4	P - 1-7/8 - 4
Reticuline	CV - 3-1/4 - 4-1/4	45° - 2-1/4 - 4	45° - 2-1/4 - 4	30° - 3-1/4 - 4	45° - 2-1/4 - 4
P - 1-1/8	30° - 3-1/4 - 4	30° - 3-1/4 - 4	30° - 3-1/4 - 4 Reticuline		Reticuline 30° - 3-1/4 - 4

FIGURE TITLES

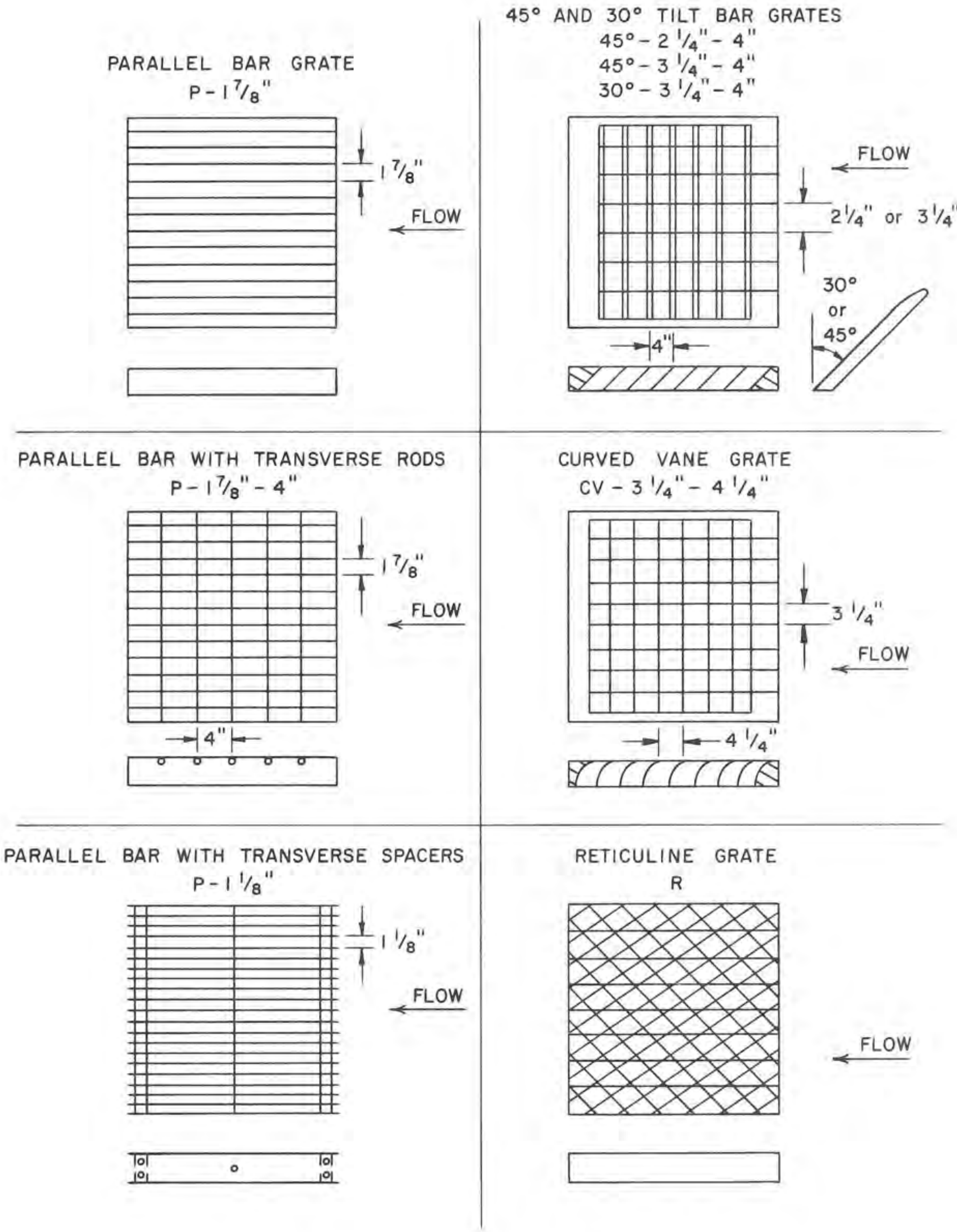

Figure 1. - Schematic drawing of the grate inlets tested (1 m = 3.28 ft, 1 mm = 0.04 in).

Figure 2. - Severe skidding in turn.

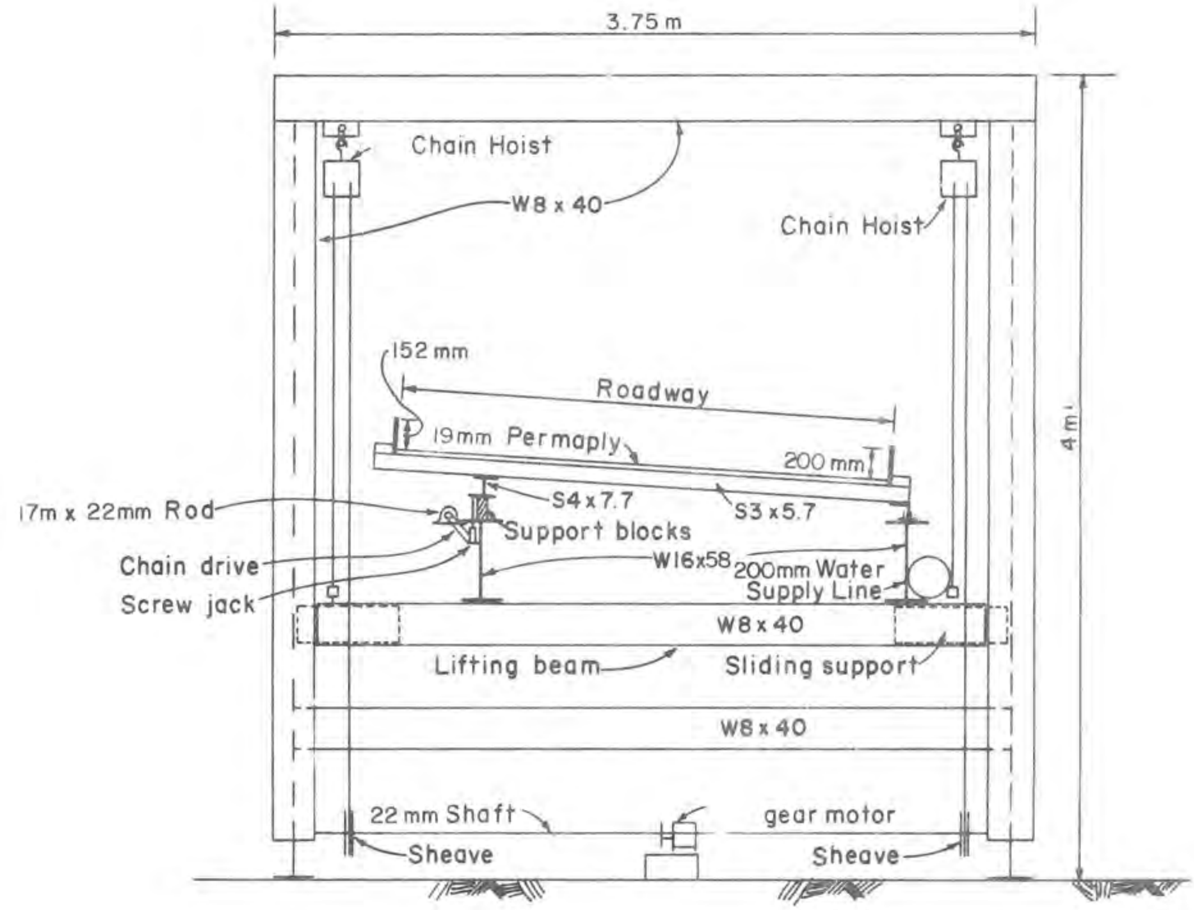

Figure 3. - Hydraulic test facility - elevation view (1 m = 3.28 ft, 1 mm = 0.04 in).

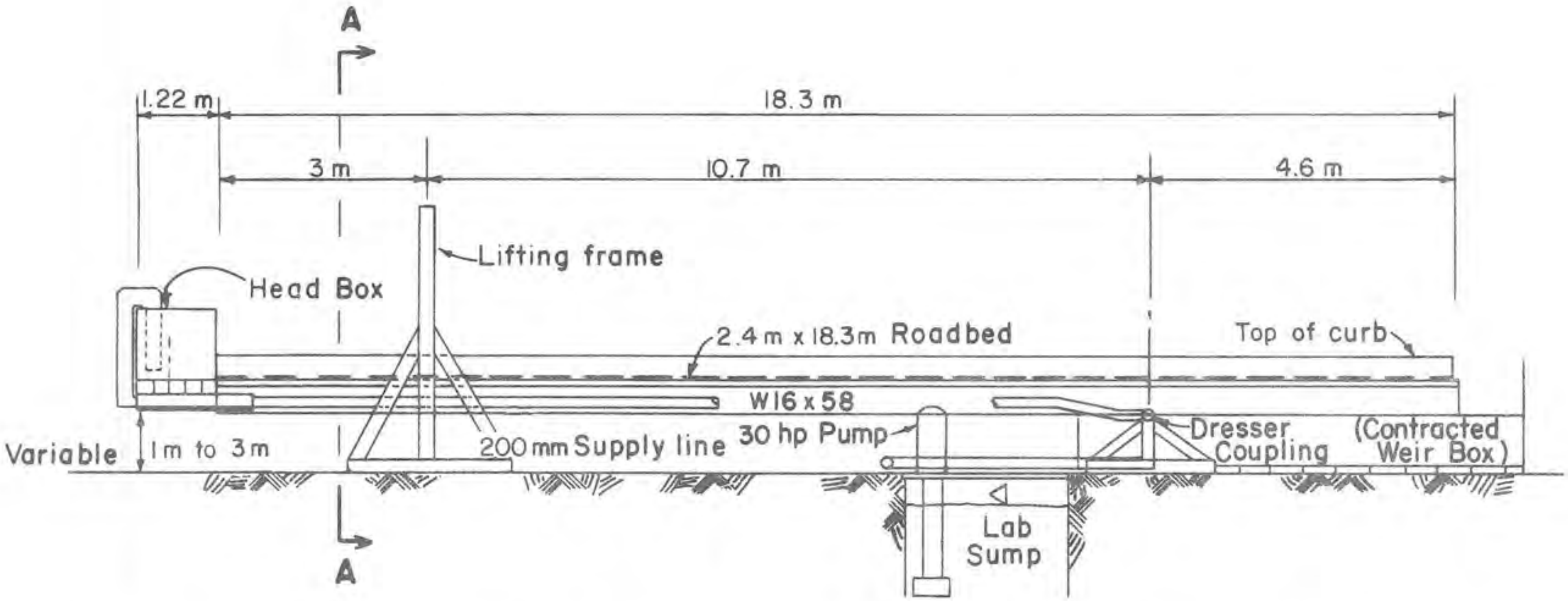

Figure 4. - Hydraulic test facility section A-A (1 m = 3.28 ft, 1 mm = 0.04 in).

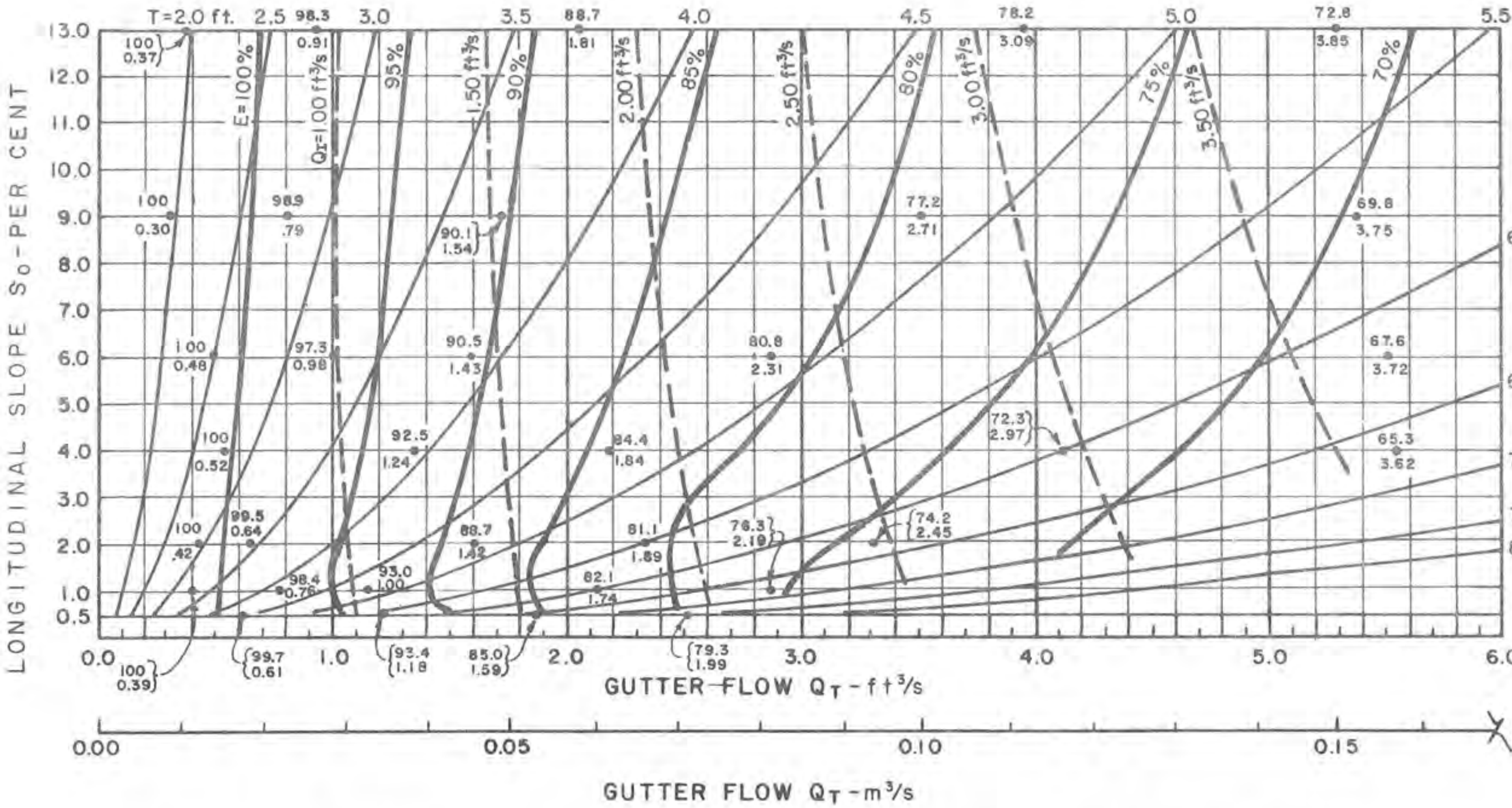

Figure 5. - Typical inlet capacity curve (1 m = 3.28 ft, 1 m^3/s = 0.028 ft^3/s).

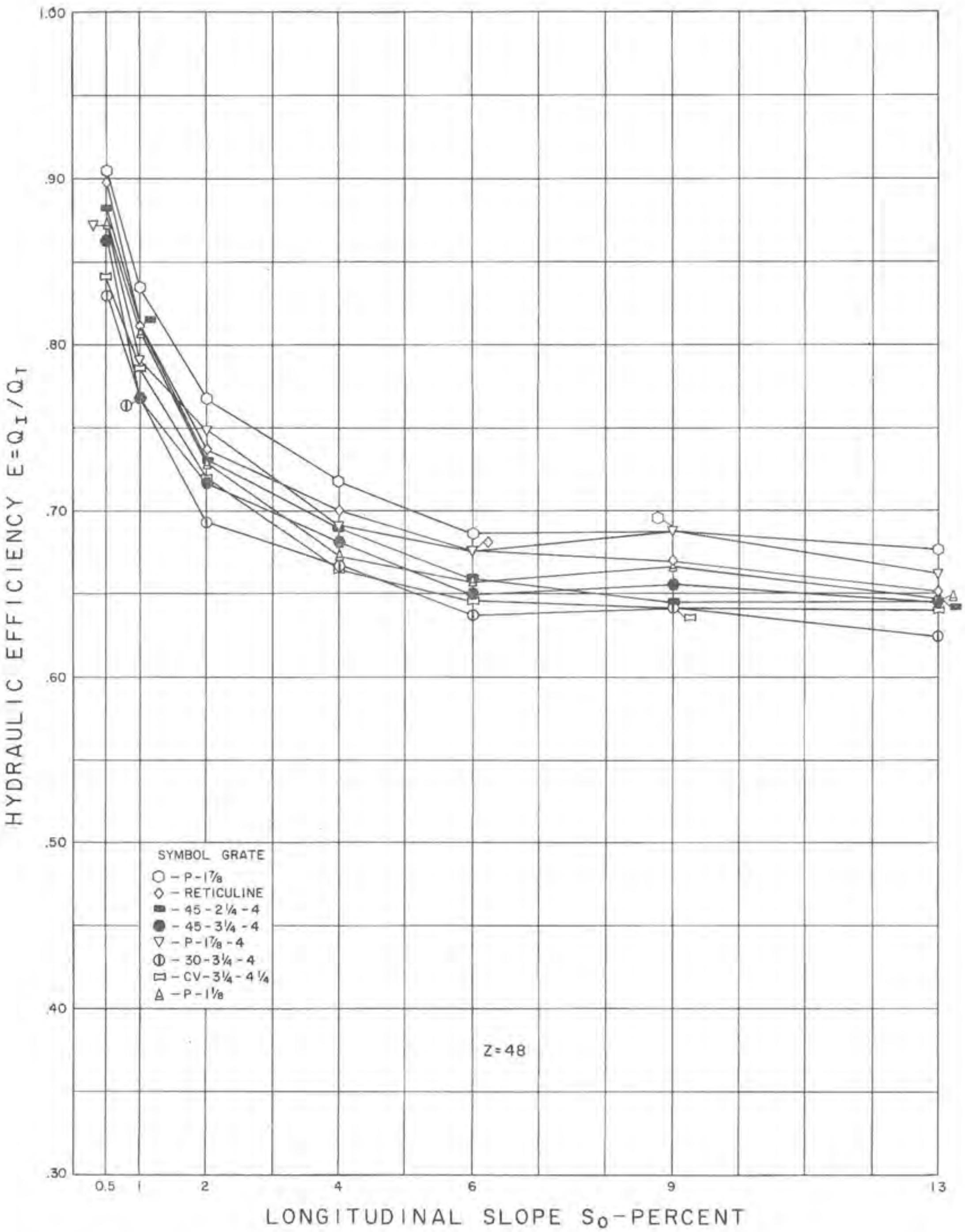

Figure 6. - Hydraulic efficiency vs. longitudinal slope T' = 2.13 m (7.0 ft), 0.61- by 1.22-m (2- by 4-ft) grates, Z = 48.

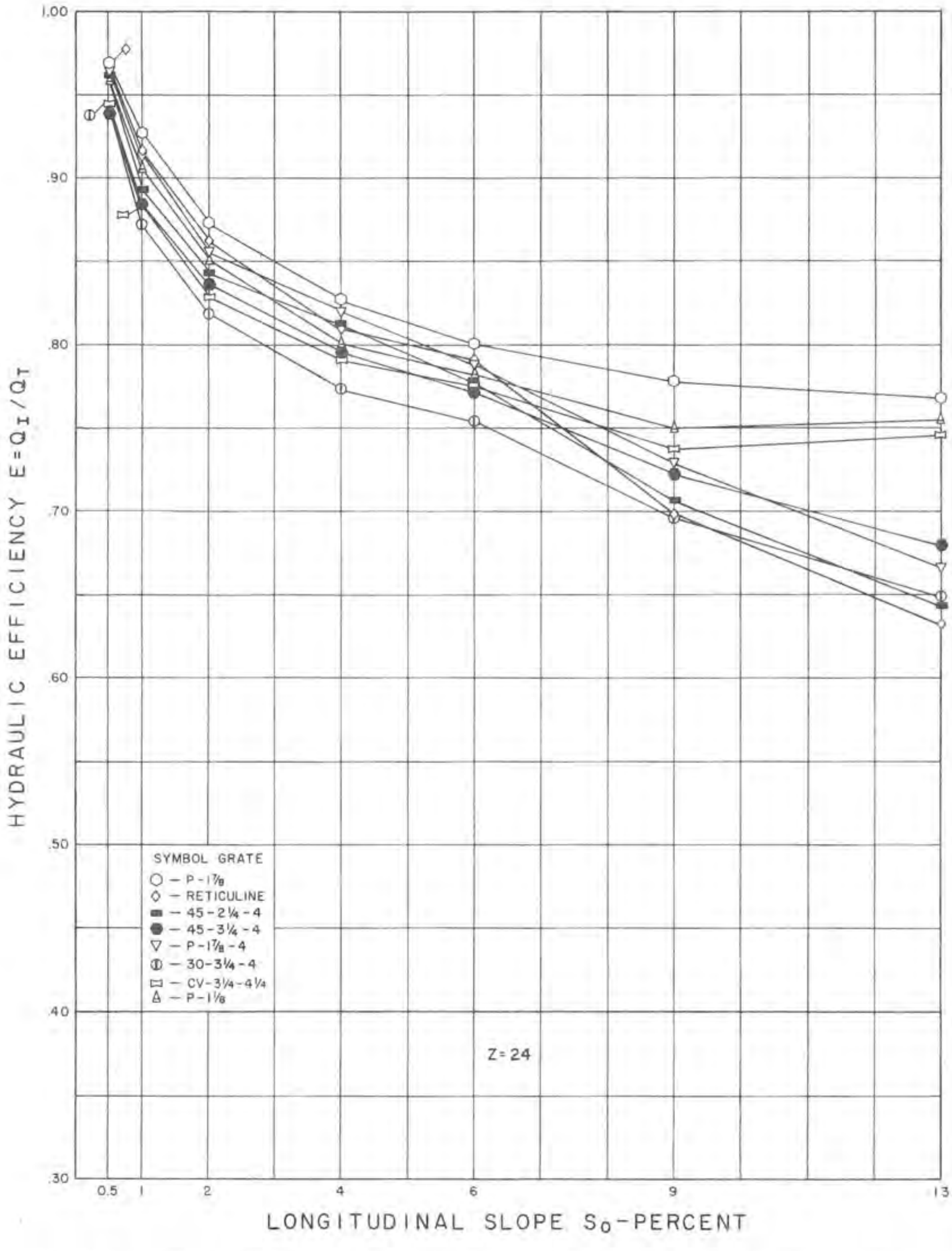

Figure 7. - Hydraulic efficiency vs. longitudinal slope T' = 1.68 m (5.5 ft), 0.61- by 1.22-m (2- by 4-ft) grates, Z = 24.

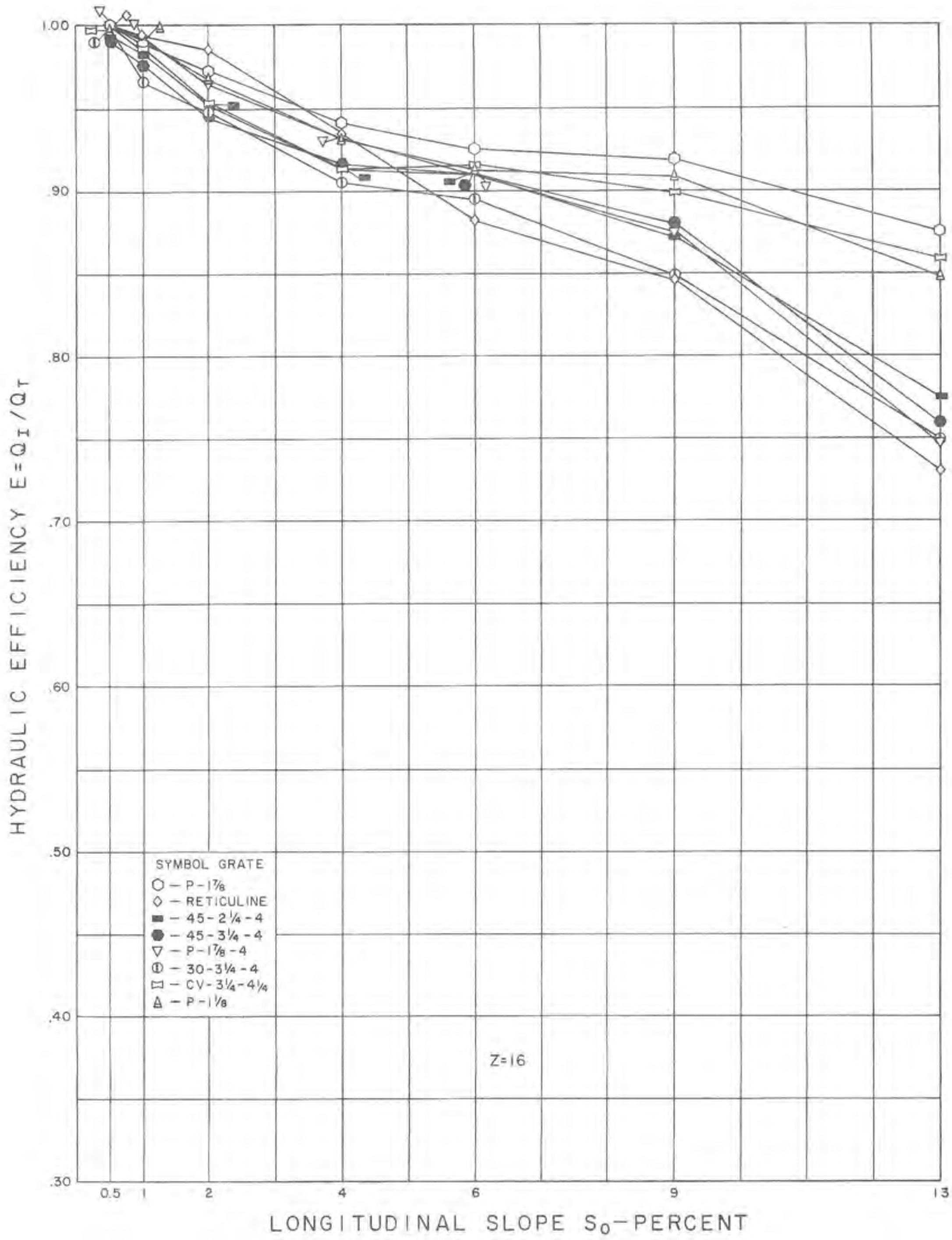

Figure 8. - Hydraulic efficiency vs. longitudinal slope T' = 1.22 m (4.0 ft), 0.61- by 1.22-m (2- by 4-ft) grates, Z = 16.