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HYDRAULIC CHARACTERISTICS OF TWO BICYCLE-SAFE GRATE INLET DESIGNS

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Final Report

FEDERAL HIGHWAY ADMINISTRATION
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16. Abstract

Two design concepts for bicycle-safe grate inlets were tested for hydraulic performance and compared to more traditional designs. The two concepts are the 45°-tilted bar and the socalled "Massachusetts Cascade" designs. The 45°-tilted bar design was tested at various sizes and bar spacings so that results for several grates using this design concept are reported. The traditional designs used for comparison included one of Oregon's standard longitudinal bar grates (with a bar spacing of 1 3/4") and an Oregon standard transverse bar grate (with a bar spacing of 2"). One special vertical-bar design was tested to isolate the effect of tilting the bars. Where ever possible, grates were tested full size, otherwise a 1:1.27 model scale was used.

For the conditions studied in this study, the test results show that these two bicycle-safe grate inlet designs have hydraulic efficiencies comparable to those of Oregon's standard longitudinal bar grate. The longitudinal (or parallel) bar grate is generally considered as the most efficient type. They offer a reasonable alternative. Research will be needed for further development of optimum designs of these two design concepts.

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UNITED STATES GOVERNMENT

Memorandum

DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

DATE: February 28, 1975

In reply refer to: HRS-42

SUBJECT: Transmittal of Research Report No. FHWA-RD-74 -77 "Hydraulic Characteristics of Two Bicycle-Safe Grate Inlet Designs"

FROM : Director, Office of Research
Washington, D.C. 20590

TO : Regional Federal Highway Administrators
Regions 1, 3-10, 15

The subject report will be of interest to those individuals in transportation agencies and in local and municipal governments confronted with designing grate inlets to accommodate bicycle traffic. The report presents experimental results obtained in the FHWA hydraulics laboratory before it had to be vacated. The study was initiated because of increasing interest in bicycles as a mode of transportation.

Distributed with this memorandum are sufficient copies of the report to provide a minimum of two copies to each regional office, two copies to each division office and four copies to each State highway agency. Direct distribution is being made to the division offices. Additional copies for official use may be requested from Mr. David Solomon, Chief, Environmental Design and Control Division, FHWA, HRS-40, Washington, D.C. 20590. Additional copies for the public are available from the National Technical Information Service, Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22151. A small charge will be imposed for each copy ordered from NTIS.

Charles F. Scheffey

Charles F. Scheffey

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INTRODUCTION

Previous studies (1, 2, 3) show that the longitudinal (parallel) grate has the highest degree of hydraulic performance and self cleaning ability. Early design of and research on grate inlets were done for all practical purposes, with only the horse, automobile and pedestrian in mind. Now in this age of environmental conscience there are more bicycle riders in the United States than ever before. Their safety has become of paramount concern, and under some conditions many of the standard drainage grates in use are a threat to their safety.

Two immediate solutions have been suggested: One is to reduce the spacing of the longitudinal bars, and the other is to turn the longitudinal bars 45° or 90° to the direction of the gutter. Any attempt to reduce the size of the openings of the longitudinal bars to less than the present narrowest bicycle tires (1/2 inches or 1.27 cm) or to turn the bar direction (1, 2, 3, 4, 5) will not only greatly reduce the hydraulic efficiency but also cause blockage by street debris thus causing street flooding. This may create a dangerous condition for automobiles, cause flood damage to adjacent property, and sometimes, inflict considerable economic loss to the community.

Where the problem is to revamp an existing highway system to make it acceptable for bicycle traffic, the number of feasible alternatives are very restricted. There are very few square grates on highways so turning bars 90° is not a simple matter of having a maintenance project to rotate existing grates. It would be too costly to recast existing openings or to increase the number of grate inlets. The only reasonable solution is to exchange existing grates with new ones of the same size, with a modified bar configuration that can afford the desired degree of safety with comparably high hydraulic efficiency of the inlets. To accomplish such an exchange designers need information to relate bar configurations to hydraulic efficiences for various street slopes.

For design of new drainage systems, there is the opportunity to increase the frequency and size of grate inlets. Selection of grates that have poor hydraulic efficiences or high maintenance requirements would result in greatly increased total costs for the drainage system.

Ideally a grate should be:

1. Safe for bicycles and pedestrians.
2. Structurally sound.
3. Hydraulically efficient.
4. Self cleaning.
5. Economical.

The primary impetus for this study is to satisfy both bicycle safety and hydraulic efficiency. Two new designs that were judged to be "bicycle-safe" were developed and provided for test. Drawings for the 45° tilted-bar, TB45, design were supplied by the Office of Federal Highway Projects, Region 10, FHWA. The Massachusetts Cascade grate, cast by the E. L. LeBaron Foundry Company (which also has a patent on the "cascade" design) in Brockton, Massachusetts, was furnished by the Massachusetts State Highway Department. This report presents the test results of the hydraulic performance of these two new designs.

LABORATORY TESTING

Experience (1, 3) indicates that a grate inlet is primarily effective in intercepting that portion of gutter flow within the width of the grate. The efficiency of a grate for intercepting all or a part of this portion of gutter flow depends mainly on the configuration and length of the grate, and the longitudinal slope of the road. Any kind of transverse element on a grate tends to cause water to splash and skip over the grate, especially on steep slopes. The complicated mechanics of flow in the grate inlet area prevents an analytical computation of hydraulic efficiency of a grate; therefore, laboratory testing is generally employed.

Selection of Model Scale

Since unusually thin depth of flow occurs in gutter and street sections, any model scale less than 1:1 in a laboratory study will distort the dynamic simulation flow regimes of the prototype field conditions and may introduce errors in the interpretation of test results. In order to avoid this source of error, a full-scale model is normally employed whenever possible. If this is not attainable, then the model scale should not be less than 1:2 to minimize the scale-induced error. Most of the grates reported were tested full size. Where scaling was necessary, a 1:1.27 scale model was used to attain the largest possible model of the largest grate.

Experimental Arrangement

The entire experimental study was carred out in a modified existing flume 29 feet long and 35 inches wide. Photo 1 shows the laboratory arrangement. The incoming gutter flow was measured by venturi meter for small flow and an annubar flow meter for larger flow. The portion of the gutter flow which by-passed the inlet was recorded by a weir. Point gages were employed to measure water depths of flow in the flume as well as the weir head.

Test Conditions

Because of limitations of time for construction and laboratory facilities the flume tests were restricted to the following parameters:

Incoming gutter flow -- Varying from 0.3 cfs to 3.2 cfs (008 m /sec to .091 m /sec).

Longitudinal slope -- Varying from .005 to .130.

Cross slope -- Fixed at an average slope of 1:25.

Transition area -- The locaction and size were fixed (as shown in figure 2 located at the end of the text) for all tests.

Surface roughness -- The average street surface was simulated by enamel paint on wooden surface.

Gutter section -- Fixed as shown in figure 2.

Grate -- Depressed 1 1/2 inches (3.81 cm) as shown in figure 2

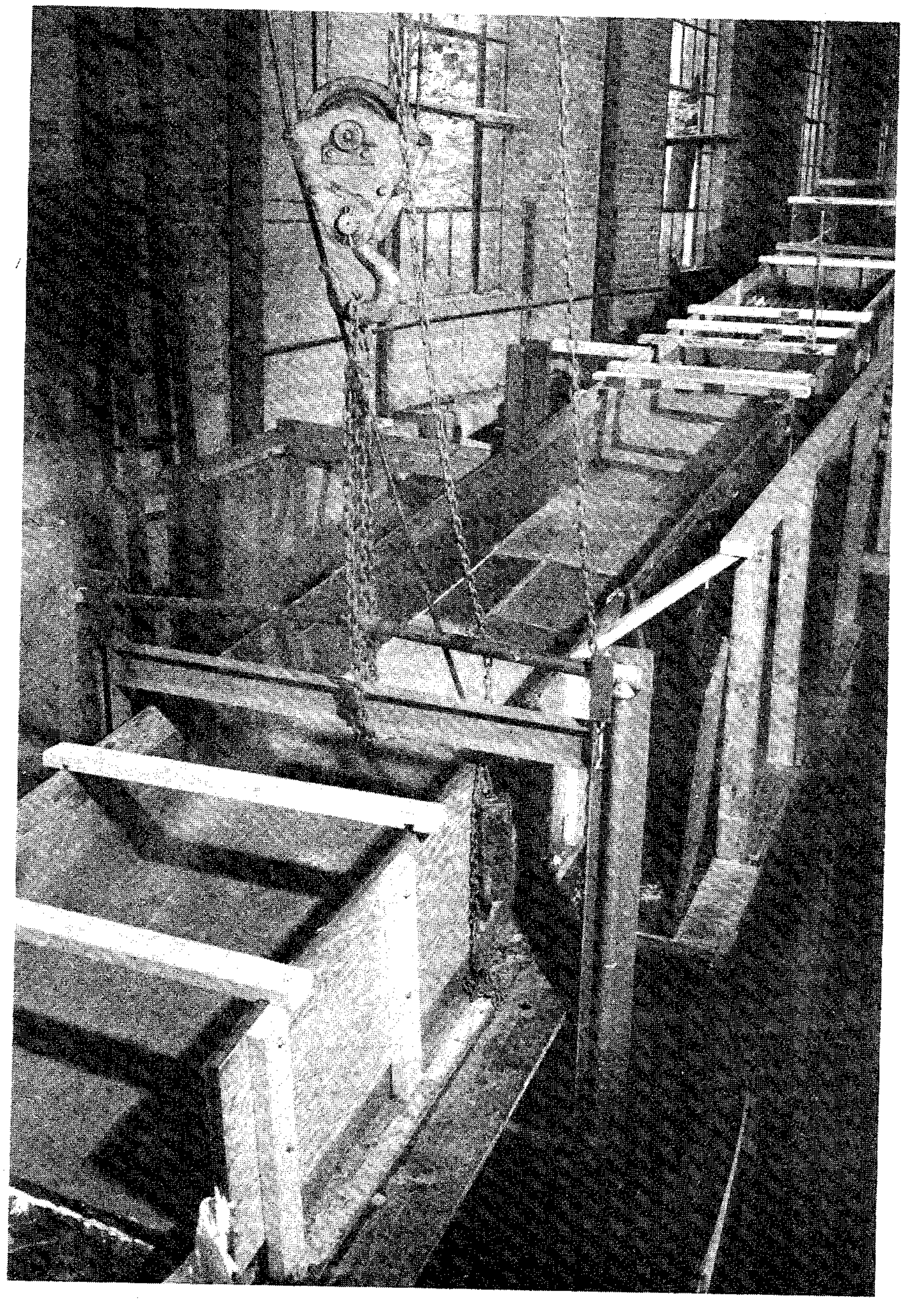


PHOTO 1. LABORATORY ARRANGEMENT

Grates Tested and Projected from Model Data

The primary impetus for the study was the evaluation of the two grate design concepts: the 45° tilt design and the Massachusetts Cascade design. To insure that a reasonably comprehensive analysis was undertaken, however, it was necessary to test and/or to evaluate analytically a large number of grates.

The testing program included six general grates and/or test categories as follows: First, a longitudinal bar grate (ORE-L), a transverse bar grate (ORE-T), and a 45° tilt bar grate (TB45-1) were all tested fullsize and at the same nominal overall size. Second, the larger size version of the 45° tilt grate, for which design curves were desired, was too big to fit the frame in the laboratory flume; so a 1:1.27 scale model (TB45-3), designed to maximize the dimension constrained by the frame, was tested and the data were projected analytically to the full size (TB45-5). Third, in order to evaluate the effect of the 45° tilt, tests were run on a 1:1.27 scale model of a grate (TBV-3), which was similar to the tilted bar grate, TB45-3, in every respect except having vertical instead of tilted bars. The data from this model were projected to a prototype (TBV-5) similar to the TB45-5 grate. Fourth, since there are difficulties in projecting data from model to full size, the (ORE-T) grate was selected rather arbitrarily as one which could be tested at both the 1:1.27 scale and in full size. Data from the scale model (ORE-T, MODEL) was projected to full size (ORE-T F.S.) which was in turn compared with the tested full size version, (ORE-T) These particular tests and comparisons are not presented herein; rather they were used to derive adjustments to augment the analysis used for other grates to project from model to full size. Fifth, a grate to vary width only of the 45° tilt concept was tested at the 1:1.27 scale (TB45-X MODEL) and projected to full size (TB45-X F. S.) The width variance (approximately 13 cm) was too slight to show up in the results; so the results are not reported herein for those two grates. Lastly, the Massachusetts Cascade grate was a manufacturer's casting and it was tested as received with no variations in size or bar configurations.

Including the grates for which data were projected, there were 12 grates involved in the study as illustrated in the schedule of grates shown in Figure 1. As noted above some of the test results did not add significantly to the report; so results from only eight of the 12 are reported. Photo 2 shows the six grates that were tested in the flume and for which results were worthy of being included in this report, the other two grates reported are not shown in the photographs because data were derived analytically; so the grates were not actually fabricated. Each of the shots of photo 2 are taken from the upstream side of the grate. Figures 1 to 9 show the detailed dimensions of the eight grates reported and their inlet conditions. Note from Figure 9 that the Massachusetts Cascade grate has the advantage of a grid pattern which would be desirable and where bicycle traffic from two directions and pedestrian safety are involved.

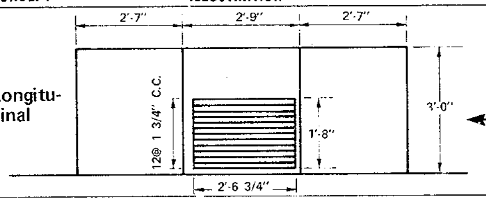
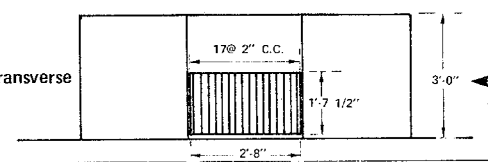
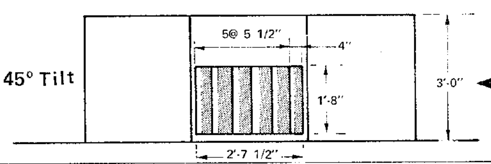
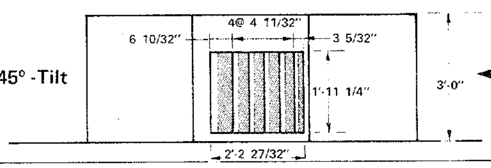
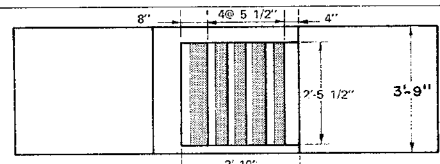
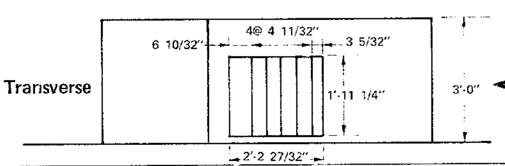
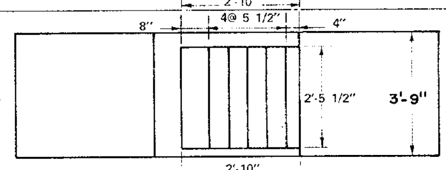
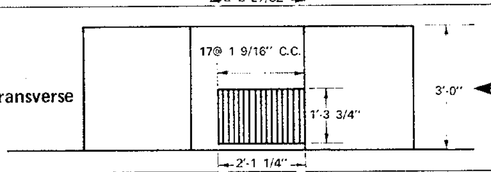
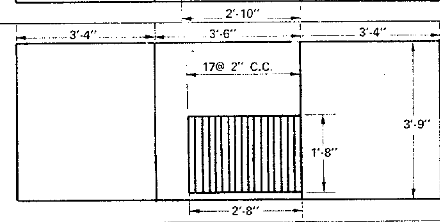
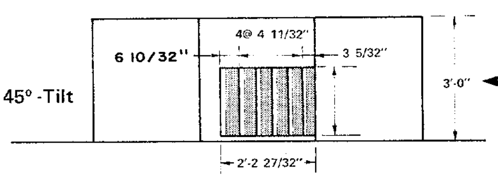
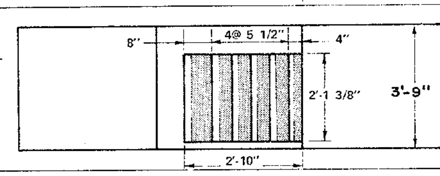
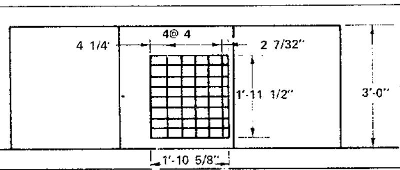
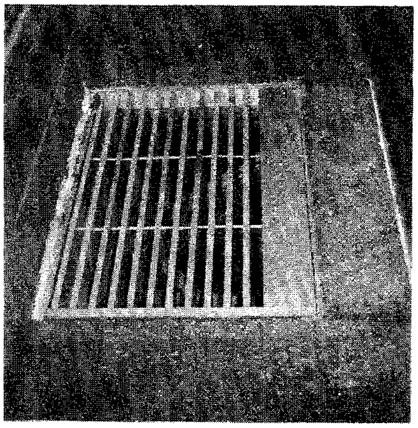
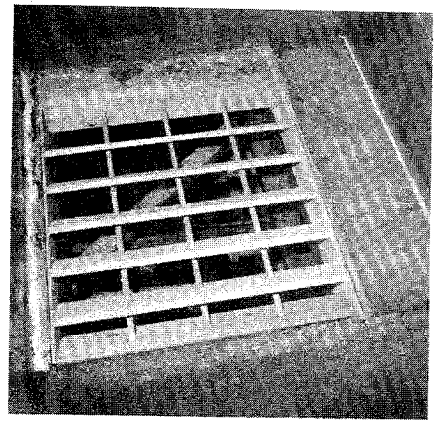
GRATES TESTED			GRATES FOR WHICH DATA WERE PROJECTED		CONTRIBUTION TO EXPERIMENT
NOMENCLATURE	CONCEPT	ILLUSTRATION	ILLUSTRATION	NOMENCLATURE	
ORE-L	Longitudinal				Comparison of various bar configurations at the same nominal overall sizes
ORE-T	Transverse				
TB45-1	45° Tilt				
TB45-3	45° -Tilt			TB45-5	TB45-5 is the full size proposed for field use
TBV-3	Transverse			TBV-5	Similar to TB45-3 & 5 except vertical instead of tilted bars. Tested to isolate effect of tilting bars.
ORE-T MODEL	Transverse			ORE-T F.S.	ORE- MODEL is 1:1.27 scale of ORE-T. Used only to augment analysis. Results are not reported.
TB45-X MODEL	45° -Tilt			TB45-X F.S.	Tested to isolate effect at varying the width in comparison with TB45-3 & 5. Inconclusive results; not reported
MASS	Mass Cascade				Working size of the cascade grate tested as received.

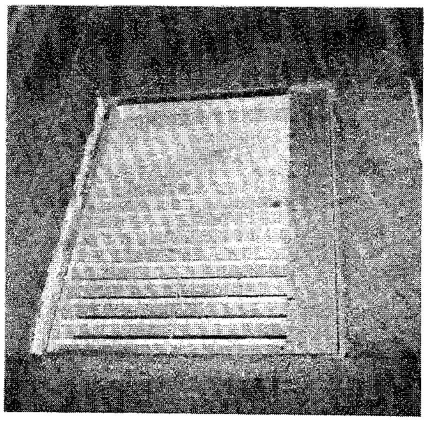
FIGURE I. SCHEDULE OF GRATES INVOLVED IN THE STUDY



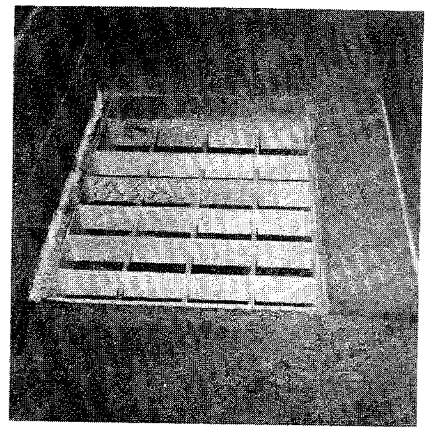
ORE–L GRATE



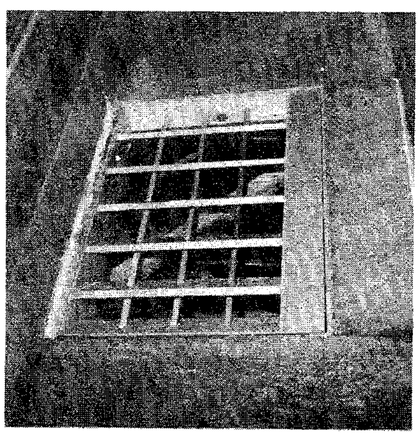
TB45–3 GRATE



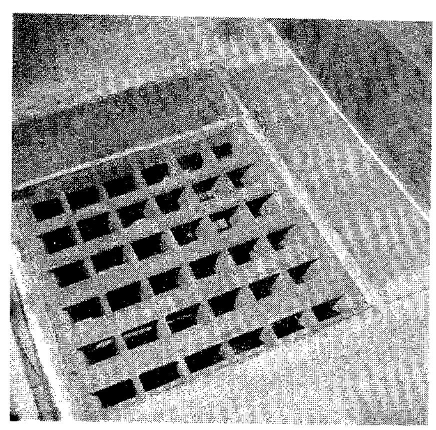
ORE–T GRATE



TBV–3 GRATE



TB45–1 GRATE



MASSACHUSETTS CASCADE GRATE

PHOTO 2. GRATE MODELS

Tests

All grates were tested on five longitudinal slopes: 0.005, 0.010, 0.028, 0.054, and 0.075. Because of time limitation, only the TB45 and Massachusetts Cascade grates were tested on a slope of 0.013. For most of the experiment, each grate at each slope was tested at six discharges distributed reasonably uniformly between a low flow near 100% interception of the grate to a high flow near the capacity of the pumps. In five cases the number of discharges varied slightly; i.e. reduced to five discharges in one case and extended to seven in four cases.

A waiting period of 20 minutes was adopted for each run to allow for the development of steady flow conditions before readings were taken. Readings consisted of incoming gutter flow, by-passed flow, water temperature, and water depth in the gutter immediately upstream from the upstream transition area. Flow conditions around the inlet area and on the grate were observed and characteristics noted. An artificial distrubance was created occasionally in the upstream gutter flow to examine its effect on grate efficiency. A 10 minute run after steady flow conditions were reached was usually adequate to obtain the required data. Test data including that not shown in this report are on file at the Environmental Design and Control Division, Office of Research, Federal Highway Administration.

ANALYSIS

Hydraulic efficiency for each grate was computed as the ratio of the flow intercepted by the grate to the total incoming gutter flow. At large flows, as the laboratory flume was only 35 inches (88.9 cm) wide, it was necessary to compensate in the analysis for the triangular cross section of gutter flow which would have been present had the flume been wide enough. The computation was made by using the modified Manning's formula as suggested by Izzard (6) as follows:

$$Q=0.56 \left(\frac{z}{n}\right) S^{1/2} Y^{8/3}$$

where "n" is the roughness coefficient in Manning's formula with respect to the composition of the gutter surface, "z" is the reciprocal of cross slope, "S" is longitudinal slope, and "Y" is water depth at the outside flume edge. An average value of n=0.013 was used. (If the equation were expressed in the metric system with Q in m^3/sec and Y in m, the "n" value would remain the same, but the coefficient 0.56 would become 0.38.)

Because gravity is the dominating force in this type of study, Froude's law was employed in computing results for full size grates from model test data. A minor adjustment was needed to derive final data for full size grates due to imperfections in the laboratory arrangement. Adjustment coefficients were determined from the verification test of the ORE-T grate at both full and 1:1.27 scale.

RESULTS

Because this is an empirical study, results are only valid within the following ranges of full scale field conditions:

Cross slope (roadway and gutter) -- 1:25

Longitudinal slope (roadway and gutter -- 0.005 to 0.130

Gutter flow -- 0 to 8.0 cfs (.226 m^3/sec)

Transition areas -- from 2'-7" x 3'-0" (.787m x .914m) to 3'-4" x 3'-9" (1.016m x 1.143m).

Extrapolation of results beyond these conditions should be discouraged. If extrapolation is attempted, consideration of basic mechanics of flow is important, and caution must be exercised if reasonable results are expected.

Figures 10 through 22 present the hydraulic efficiencies of each grate against gutter flow discharge. Figures 10 through 15 show hydraulic efficiency data for grates ORE-T, ORE-L, Massachusetts Cascade, and TB45-1, 3, and 5. Figures 16 through 20 compare the test results of 45° tilted transverse bar grates against their vertical bar versions. Figures 21 and 22 present test results of the TB45-5 and Massachusetts Cascade grates, respectively, for all six slopes. The experimental results of all eight grates are summarized in Appendix A.

Photos 3 through 9 show the grates under test conditions on slopes of 0.005 and 0.075 and under low and high gutter flow conditions. Photo 6 shows the TB45-3 grate also being tested on a slope of 0.028. Photos 8 and 9 show the Massachusetts grate also being tested on slopes of 0.028 and 0.013, respectively.

At the flat slope, 0.005, none of the grates were completely covered with water for any of the gutter flows. On steep slopes, .075, and greater, none of the grates were completely covered with water at the low flows with upstream spread approximately equal to the grate width, and only for the maximum flow of 3.2 cfs (0.0906 m^3/sec) were almost all the grates covered with water. The generally incomplete grate coverage and corresponding contribution of water from beyond the grate width points up the inadequacy of design methods and test results based only on the approach flow over the width of the grate.

Water skipping and splashing were virtually nil for the very flat slopes, especially the .005 slope, and were noticeable at all only for the two transverse bar grates, ORE-T and TBV-3. For steep slopes, splashing was noticeable for all grates but was worst for TBV-3, and skipping or skimming was especially prominent for the grates with transverse bars (ORE-T, TBV-3, and MASS). At the .075 slope and at the flow of 3.2 cfs (0.0906 m^3/sec) water skipped over the bars of the ORE-T grate so completely that hardly any splashing was observed.

DISCUSSION OF RESULTS

Hydraulic Efficiency

To a certain degree, the hydraulic efficiency[1/] of a grate depends on the spacing of its bars. The wider the space between the bars, the more water will flow into the spaces. A survey of standard drawings from a number of States involving the use of longitudinal-bar grates indicates that bar spacing ranges from 1 to 2 3/4 inches (2.54 to 6.98 cm). For purposes of this study, the Oregon design standards for longitudinal-bar and transverse-bar grates were used as a basis of comparison of the new grates. Use of the Oregon design standards should not be interpreted as FHWA perference over those of other States. Furthermore, favorable comparisons for the new design concepts relative to the longitudinal-bar grate are restricted to the bar spacing tested (1 3/4 inches or 4.44 cm) and smaller. These comparisons cannot be generalized for longitudinal-bar grates with larger spacings used by other States.

Figures 21 and 22 show that the most efficient slope is not the flattest slope. This rather unexpected observation, can be explained by the fact that hydraulic efficiency depends upon width of spread as well as approach velocity of the gutter flow. Although a decrease in longitudinal slope lowers the approach velocity, it also increases the spread. At a slope of approximately .010 a further decrease in longitudinal slope does not result in improved hydraulic efficiency.

1/Hydraulic efficiency is defined as the ratio of flow intercepted by the grate to the total flow in the gutter.

Grate TB45-1 tends to be more hydraulically efficient than grates TB45-3 and TB45-5 on steep slopes (Figures 11 and 12). One would expect grate TB45-1 to be the least efficient because it is the narrowest of the three. The inconsistency is a result of other factors that influence hydraulic efficiency. Grate TB45-3 is wider, but also shorter and has narrower spaces between the bars. Although grate TB45-5 is larger, the distance between curb and grate opening is greater, permitting more

Hydraulic efficiency of a grate is dependent upon length and width of the grate, bar spacing, size and shape of the transition areas, gap width between the foot of the curb and the grate, and transverse and longitudinal slopes of the street. It is difficult, therefore, to predict the effect of changes in one or a combination of these factors on the hydraulic efficiency of any given grate without a much more extensive testing program. Research being planned by the Federal Highway Administration is designed to fill these gaps.

The hydraulic efficiencies of the grates tested are compared in figures 10 through 15. Their relative hydraulic efficiencies are summarized as follows:

1. The Oregon Standard Transverse-bar Grate is, as expected, the least efficient grate of those tested for each of the five longitudinal slope conditions.
2. On small slopes, the new 45° tilted transverse-bar grates are more efficient than the Oregon standard longitudinal-bar grate.
3. On steep slopes, the Oregon standard longitudinal-bar grate is more efficient than the others tested.
4. The Massachusetts Cascade grate is almost as efficient as the new 45° tilted transverse-bar grates on slopes less than .003, but somewhat less efficient on steeper slopes.

Relative Hydraulic Efficiency

Table 1 summarizes data in figures 10 through 14, and further supports the four conclusions stated above. The relative hydraulic efficiencies of the TB45-5 basic 45° tilted transverse-bar grate, the Massachusetts Cascade grate, and the Oregon Transverse-bar grate are compared using the Oregon Longitudinal-bar grate (ORE-L) as a standard. Its hydraulic efficiency is rated 100 for each gutter flow and longitudinal slope tested. The hydraulic efficiencies of the other three grates were computed relative to the ORE-L grate.

Slope	Grate	Gutter Flow (cfs) (Equivalent Metric Units m^3/sec in Parentheses Below)					
		0.5 (.014)	1 (.028)	2 (.056)	3 (.085)	3.5 (.099)	4 (.113)
0.5%	ORE-L	100	100	100	100		100
	ORE-T	100	97	96	92		90
	TB45-5	100	105	112	111		111
	MASS	100	96	100	101		103
1.0%	ORE-L	100	100	100	100		100
	ORE-T	98	90	88	86		81
	TB45-5	100	103	104	108		110
	MASS	100	97	96	97		100
2.8%	ORE-L	100	100	100	100	100	
	ORE-T	92	88	85	82	78	
	TB45-5	102	104	106	109	103	
	MASS	100	99	98	100	101	
5.4%	ORE-L	100	100	100	100	100	
	ORE-T	83	79	74	71	66	
	TB45-5	99	97	97	102	98	
	MASS	92	86	86	86	83	
7.5%	ORE-L	100	100	100	100	100	
	ORE-T	80	75	66	64	63	
	TB45-5	98	97	92	93	90	
	MASS	89	83	81	77	74	

Table 1. Comparison of relative hydraulic efficiency of four grates using ORE-L grate's hydraulic efficiency as 100 for each gutter flow and slope tested.

Influence of Tilt and Spacing of Bars on Hydraulic Efficiency

Figures 16 through 20 illustrate the effect of the 45° tilt of transverse bars of a grate. Under all conditions investigated the hydraulic efficiencies of the tilted bar grates, TB45-3 and TB-45-5, are more efficient than the corresponding vertical bar grates, TBV-3 and TBV-5. It appears that the larger the bar spacing the more pronounced is the difference in hydraulic efficiencies for tilted versus vertical bar grates. This observation is evidenced by the larger spread between TB45-5 and TBV-5 curves than between TB45-3 and TBV-3 curves.

The laboratory experiments for this study were not designed to evaluate the effect of bar spacing for standard vertical transverse-bar grates. Although the three grates of this design (ORE-T, TBV-3 and TBV-5) have different bar spacings, their overall sizes are also different. As would be expected, the results in figures 10 through 20 show that grate TBV-5 with the larger bar spacing and overall size is the most efficient of the three and grate TBV-3 with medium bar spacing and overall size is next. Unforunately, no two grates had the same overall size and different bar spacings; consequently, it is not possible to make more than general comparisons.

Bicycle and Pedestrian Safety

Bicycle and pedestrian safety considerations must be qualified on the basis of the judgment used to determine acceptability. Although, it is anticipated that future FHWA research will delve into this aspect of the problem, there are no existing criteria for determining when a grate is bicycle or pedestrian safe.

Grates that can accommodate bicycles traveling parallel to the curb are considered to be bicycle safe. A grate with transverse bars, large enough to sustain bicycle loads and spaced sufficiently close to allow reasonably smooth passage, meets this criteria. Based on drawings of socalled "bicycle safe" grates that were submitted to FHWA by several States, spacing of transverse bars up to 6 inches (15.2 cm) are tolerated by bicyclists. Wheel diameters greater than 20 inches (50.8 cm) will span a 6 inch (15.2 cm) opening with less than a 1/2 inch (1.27 cm) vertical drop into the opening.

Both the TB45 and the Massachusetts Cascade (MASS) grates are considered to be bicycle safe. The TB45 grate will accommodate bicycle traffic only in the direction parallel to the curb. The 5 1/2 inch (14.0 cm) spacing between bars makes it a very precarious design for pedestrians. The grid pattern of the Massachusetts Cascade grate make it safe for bicycle traffic from any direction. Furthermore, the approximately 3 1/2 inch x 4 inch (9 cm x 10 cm) grid openings should safely accommodate adult male pedestrians, but certainly cannot be rated as an unqualified pedestrian-safe grate in areas where small children or women with small feet are involved.

Transverse bar grates with bar spacings of approximately 2 inches (5 cm) such as for the ORE-T grate are safe for bicycle traffic parallel to the curb but would be a "trap" for bicycle traffic in the perpendicular direction. That spacing should be small enough to accommodate most pedestrian traffic. The difficulties with such grates are that they tend to be the least efficient hydraulically and they tend to clog more easily than the longitudinal-bar grates. Table 1 shows that at flat street slopes the sacrifice in hydraulic efficiency is not so great, but transverse-bar grates should be avoided, if possible, at steeper slopes because the relative hydraulic efficiency drops considerably for slopes greater than 0.010.

Longitudinal bar grates with bar spacings of approximately 1 3/4 inches (4.4 cm) such as for the ORE-L grate are considered to be very hazardous for bicycle traffic parallel to the curb. This type of grate has been highly criticized because the spacing between bars may be as much as 2 or 3 inches (5 or 7.6 cm) and bicycle wheels may be trapped in the openings. For a given bar spacing and size opening this design is the most efficient hydraulically over a full range of slopes. Furthermore, debris tends to slide over the bars so clogging is less of a problem. Longitudinal bar grates are considered to be safe for pedestrians and with slight modifications they can probably be made safe for bicyclists. Thin transverse rods may accomplish the necessary degree of bicycle safety without seriously affecting hydraulic efficiency or self cleansing capabilities for debris. The effectiveness of such modifications are to be evaluated in proposed future FHWA research.

CONCLUSIONS AND RECOMMENDATIONS

The new 45° tilted transverse-bar grates display excellent hydraulic performance in comparison to those of the standard Oregon longitudinal bar grate and will accommodate bicycle traffic. The nearly 5 inch (12.7 cm) space between bars creates a potential pedestrian hazard and detracts from the grate as a viable alternative to longitudinal bar grates. Laboratory results do indicate, however, that a reduction in the space between bars to afford pedestrian safety may be accomplished without significantly sacrificing hydraulic efficiency. One disadvantage of narrow spacing between bars is the susceptibility to clogging by street debris. Test data on the three variations of the 45° tilted transverse-bar grate are not conclusive, although grate TB45-5 is somewhat more efficient overall.

Two important elements relative to the new 45° tilted transverse-bar grate were not examined in this study. They are the effect of varying the angle of tilt of the bars and the effect of the depressed transition area around the grate. The State of New Hamsphire has used a 60° tilted transverse-bar grate under certain highway conditions for sometime, but its hydraulic efficiency has never been determined. Various angles of bar tilt should, therefore, be tested under the normal range of street conditions to determine the best tilting angles for special and overall conditions. Past studies have conclusively demonstrated the value of depressed transition areas in increasing inlet efficiency. It has been further noted, however, that routine street resurfacing fills the depressed transition areas. From a practical point of view, tests should be run to determine hydraulic efficiencies without the depressed areas.

It is concluded that additional research is needed to develop an optimum design for the tilted transverse-bar grate concept that will be hydraulically efficient and bicycle safe. The Massachusetts Casade grate offers a possible alternative, but further research is recommended to increase its hydraulic efficiency on steeper slopes.

Because of the empirical nature of this study, the results presented there are valid only for the specific conditions under which this study was made. The hydraulic efficiencies of the Oregon Longitudinal-bar and transverse-bar grates are valid only for these special designs and should not be applied to any other longitudinal-bar and transverse-bar grate designs.

ACKNOWLEDGEMENTS

The laboratory work for this staff research was carried out in the former Federal Highway Administration Hydraulic Laboratory. Edward A. Sheldahl, a co-op student in Civil Engineering at Georgia Institute of Technology assisted in running the flume tests and processing data for computer analysis. Eric Rountree, a co-op student in Architecture at Howard University assisted in preparation of drawings for construction of the laboratory test facilities. Leonard E. Wood, Chief, Environmental Control Group and David L. Solomon, Chief, Environmental Design and Control Division, made valuable suggestions for this report and their review comments are gratefully acknowledged.

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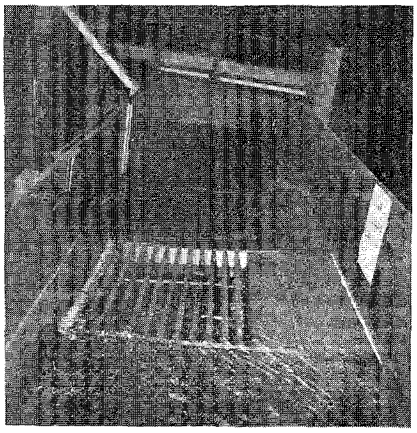

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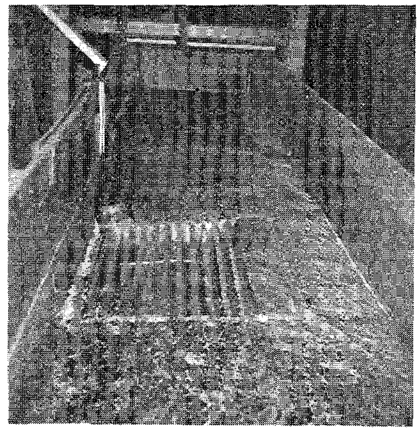

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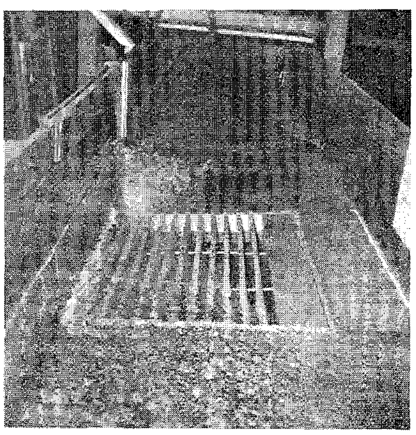

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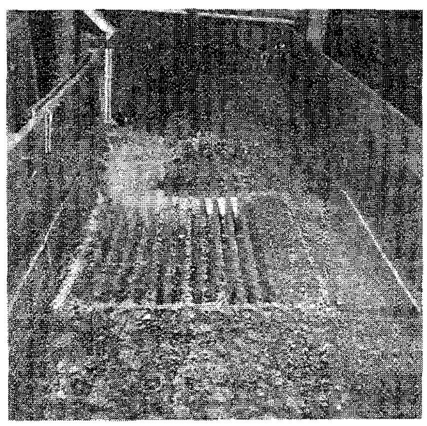

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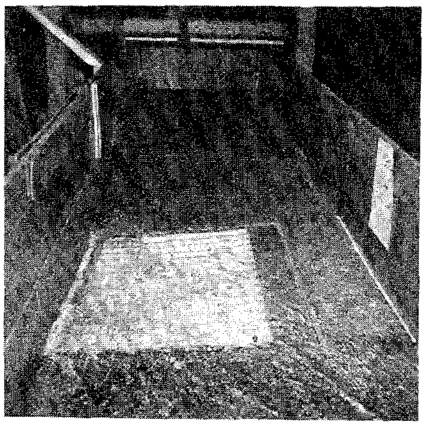
PHOTO 3. GRATE ORE-L



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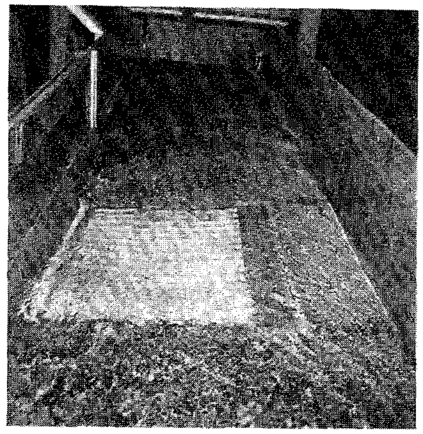

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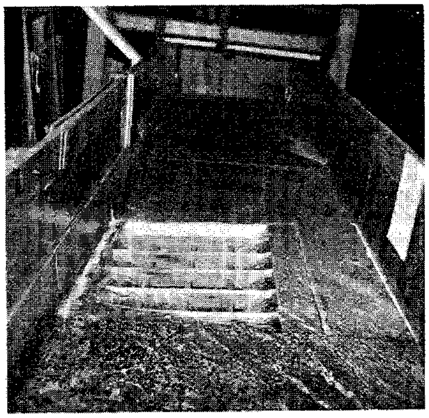
Low Flow, Slope 0.075

High Flow, Slope 0.075

PHOTO 4. GRATE ORE-T



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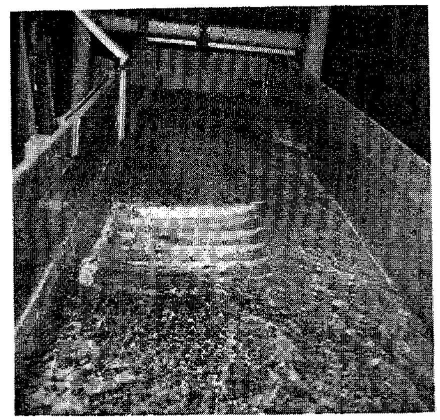

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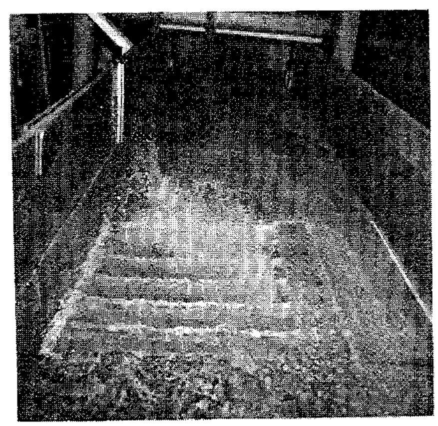

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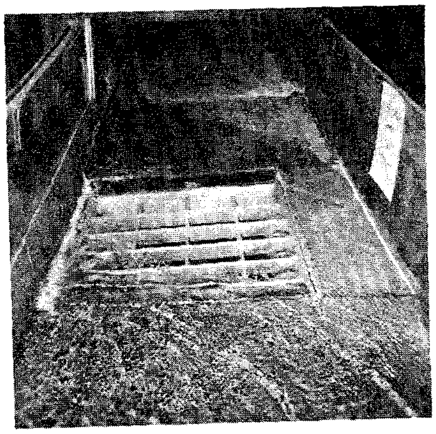
PHOTO 5. GRATE TB45-1



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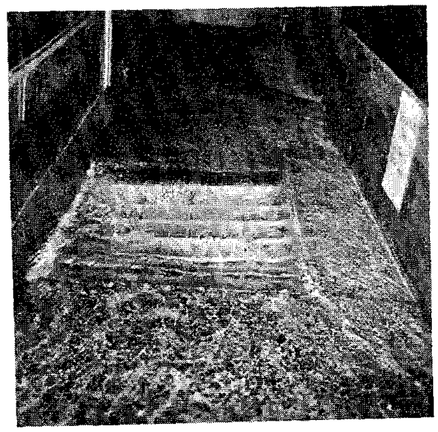

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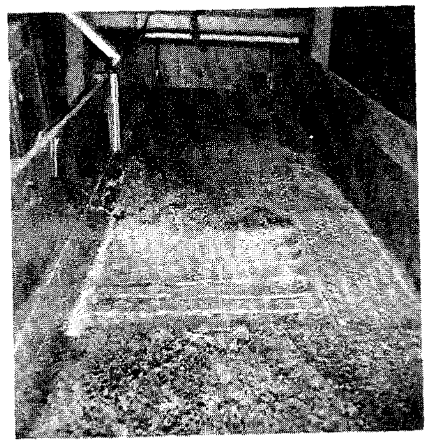
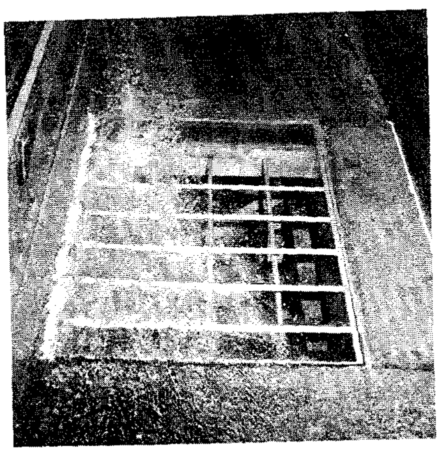


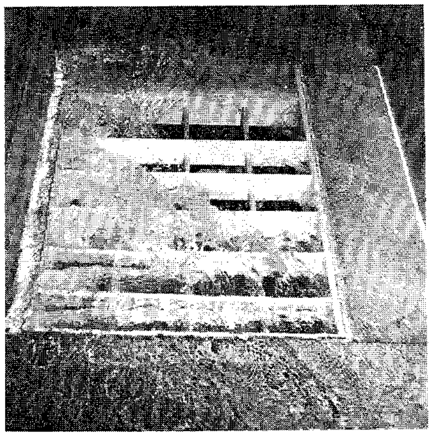
High Flow, Slope 0.028



Low Flow, Slope 0.075

High Flow, Slope 0.075

PHOTO 6. GRATE TB45-3



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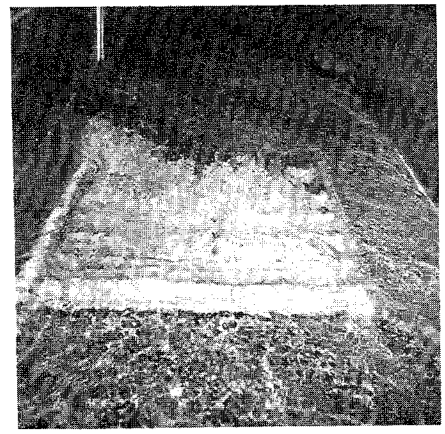

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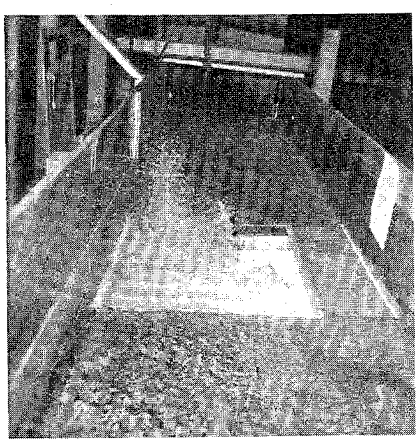

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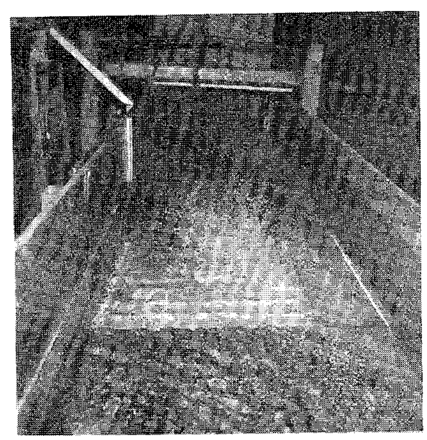

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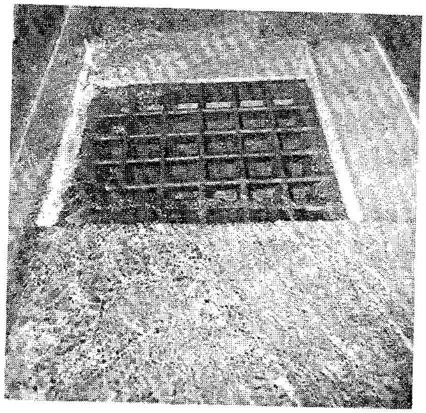
PHOTO 7. GRATE TBV-3



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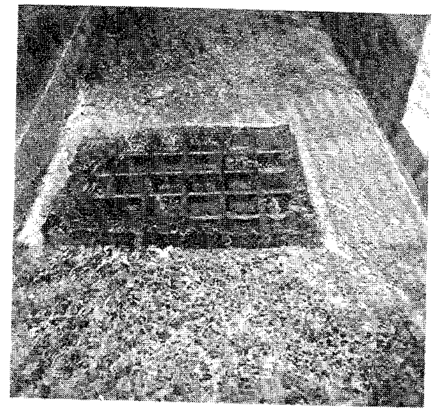

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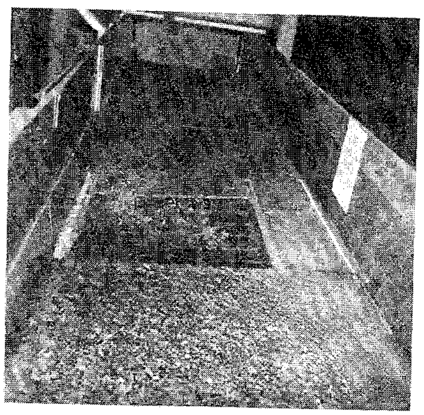

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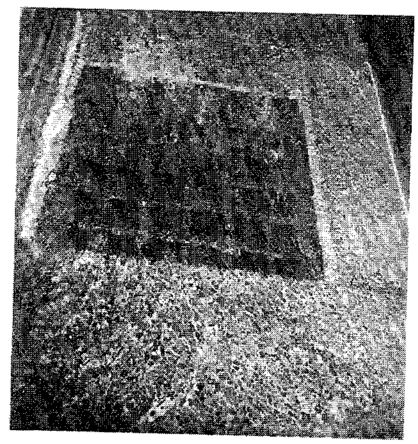

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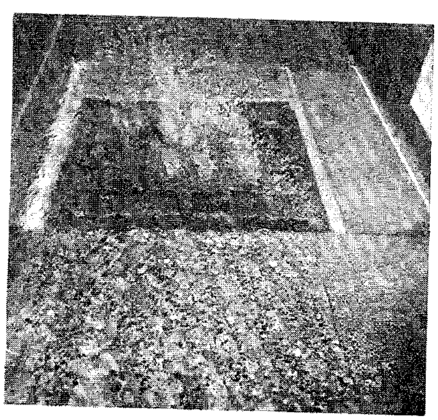

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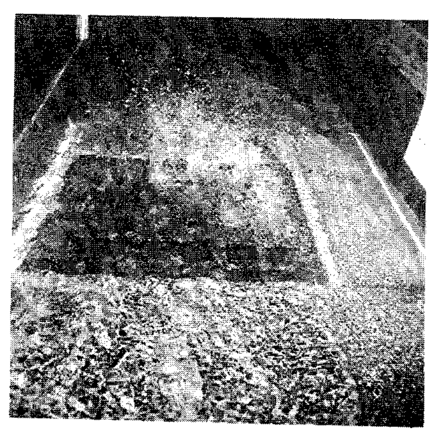
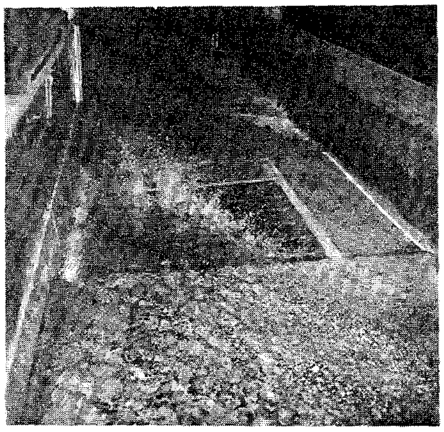


High Flow, Slope 0.075

PHOTO 8. MASSACHUSETTS CASCADE GRATE



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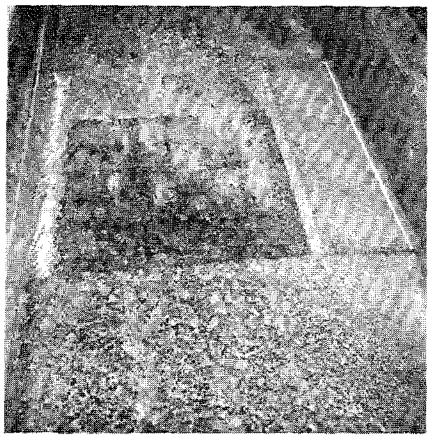

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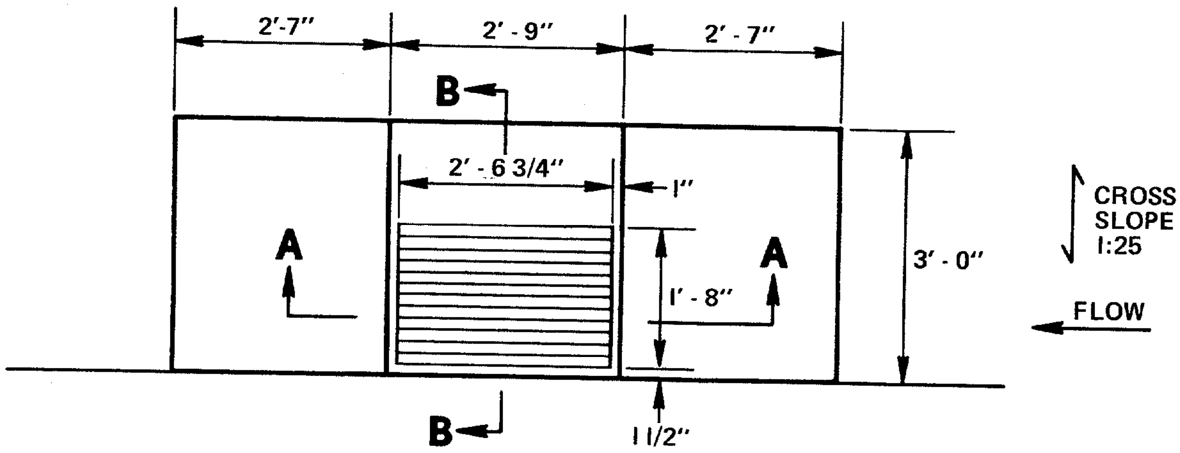
PHOTO 9. MASSACHUSETTS CASCADE GRATE (Continued)



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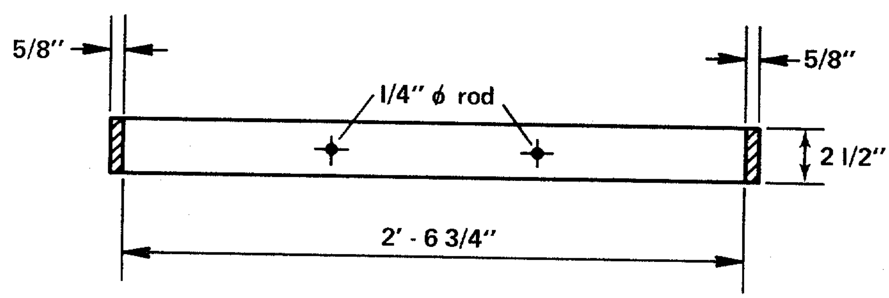
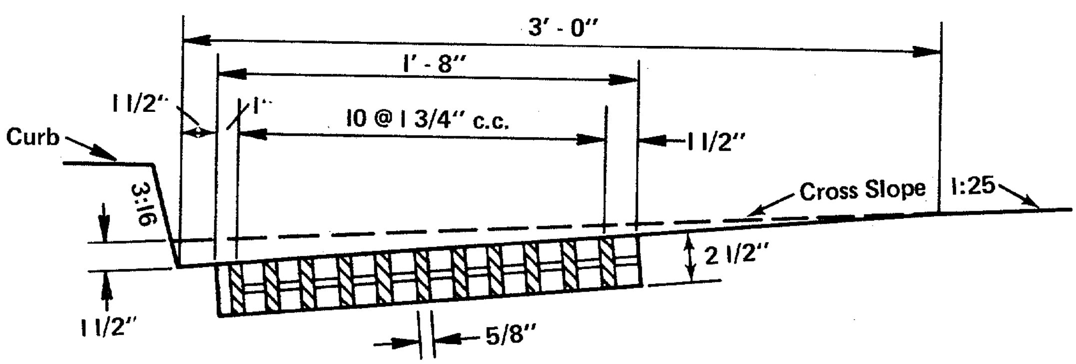


SECTION A-A



SECTION B-B

Figure 2. Oregon Longitudinal - Bar Grate (ORE-L)

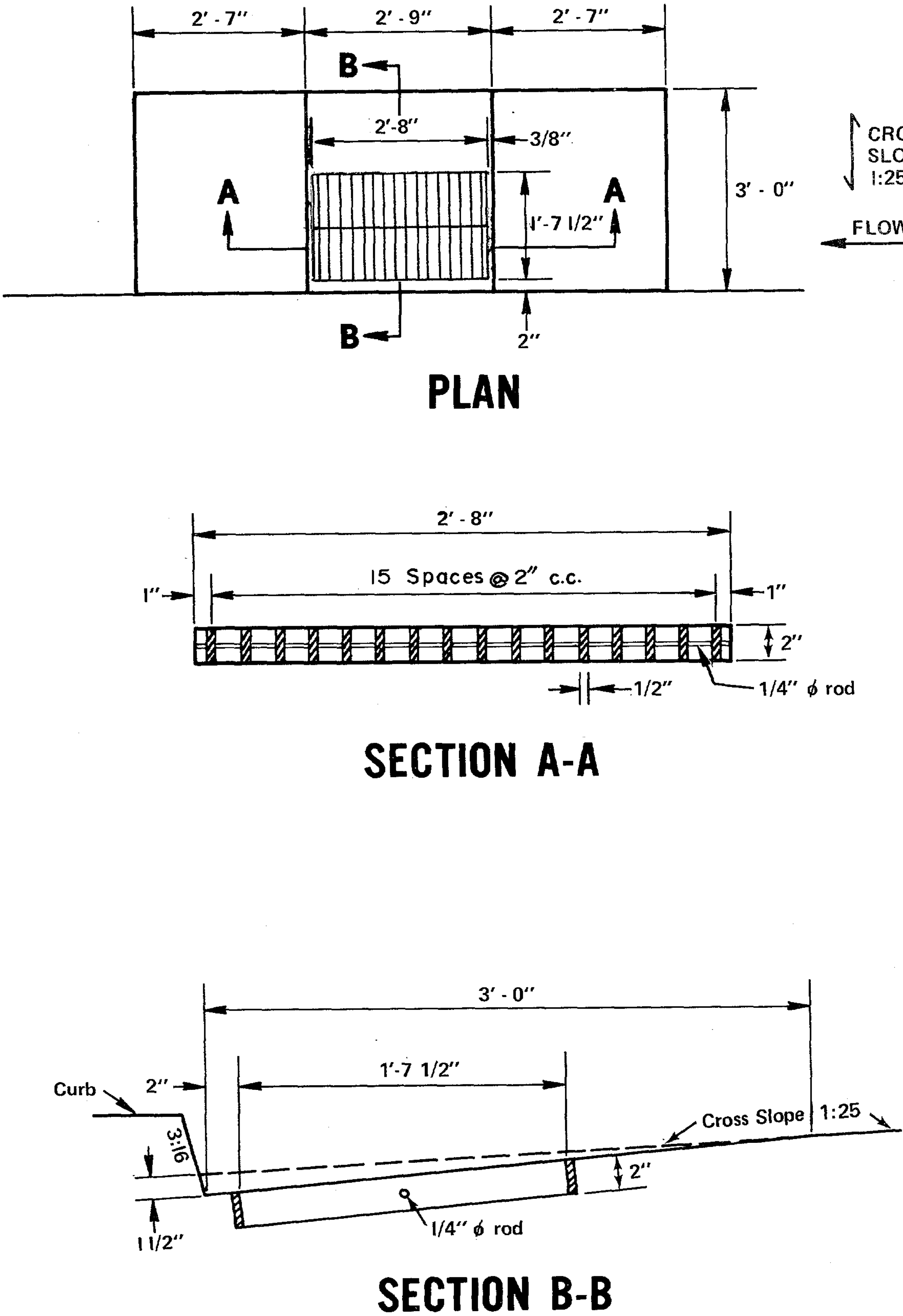
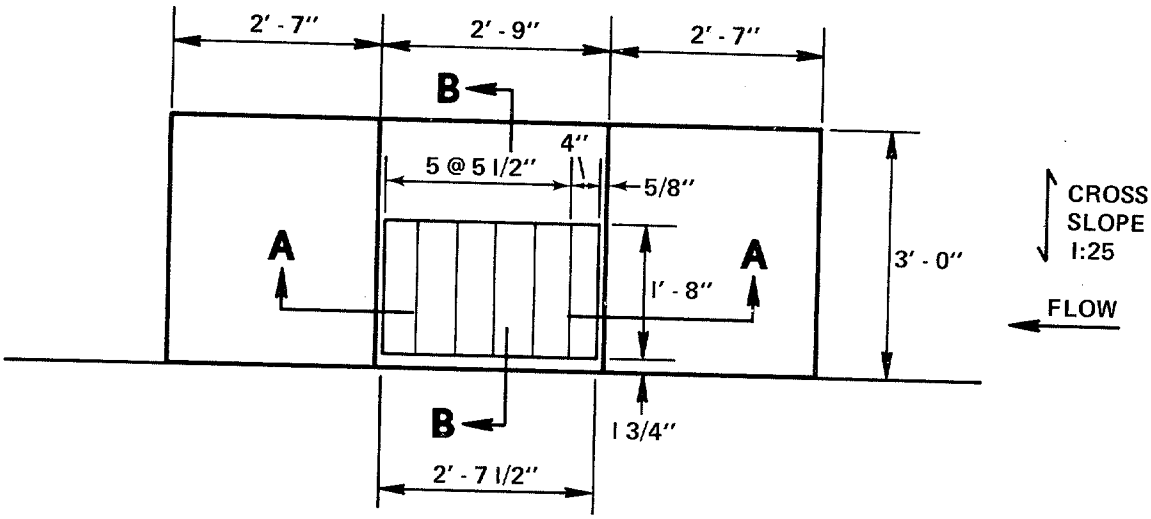


Figure 3. Oregon Transverse - Bar Grate (ORE-T)



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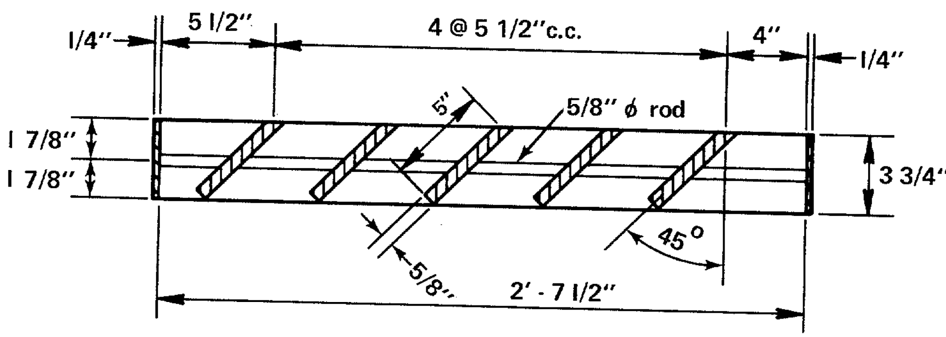

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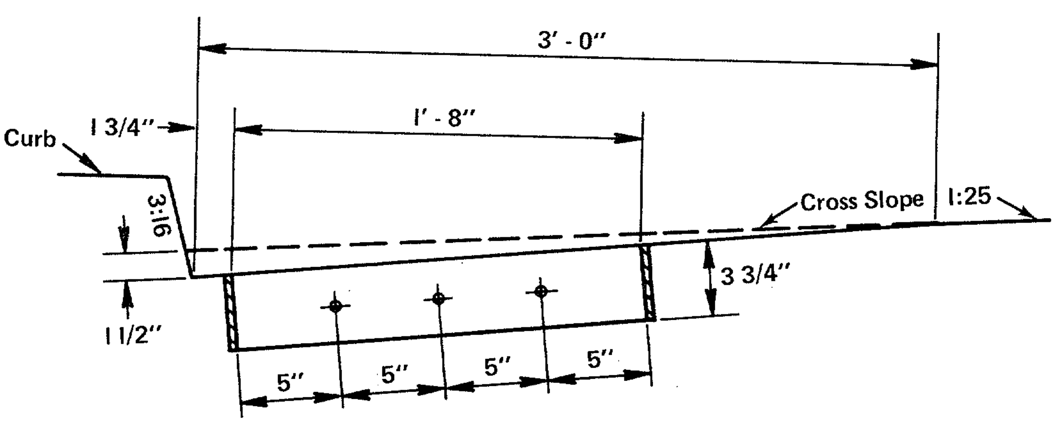


SECTION B-B

Figure 4. 45° Tilted Transverse - Bar Grate TB45-I

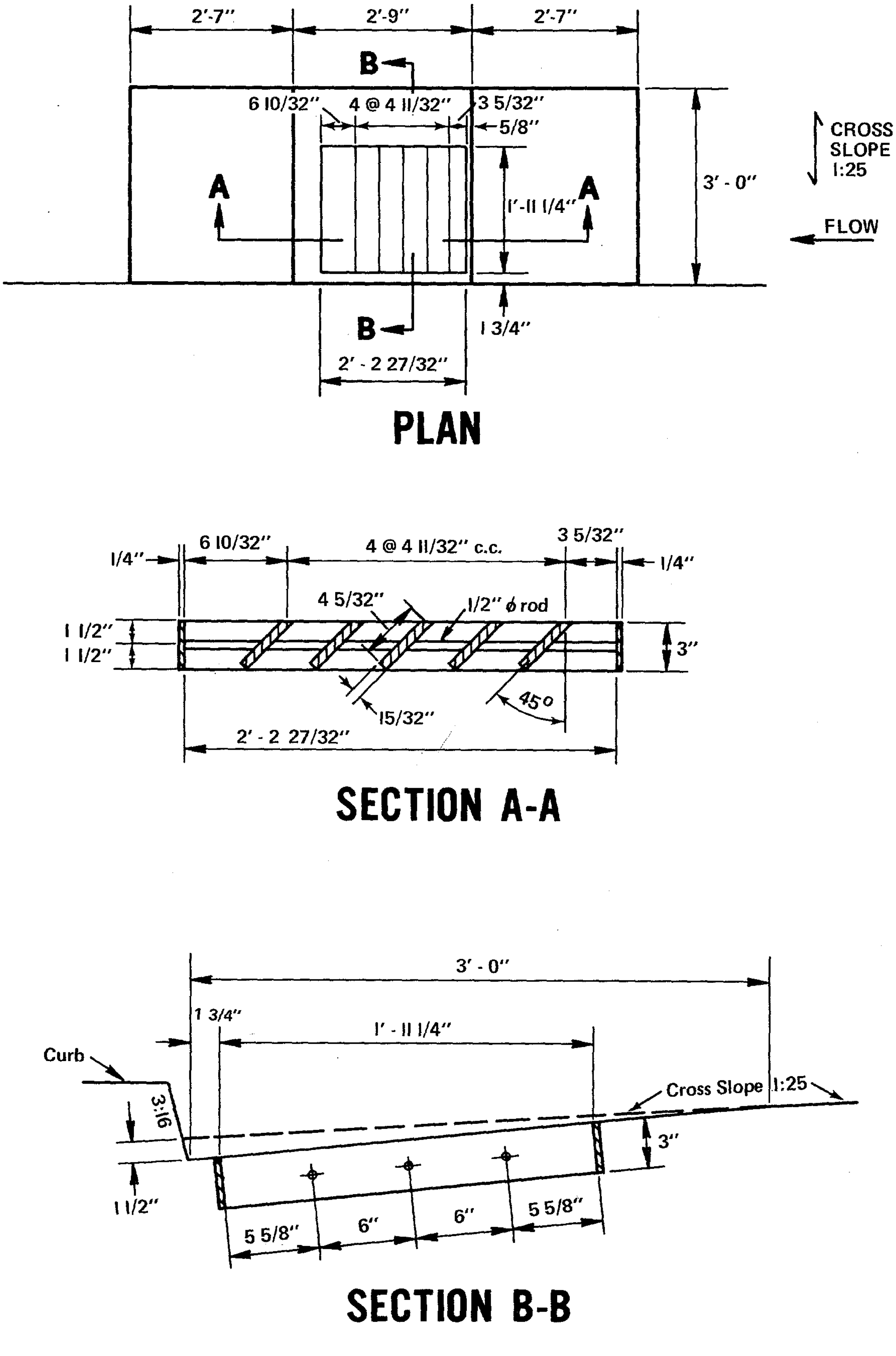
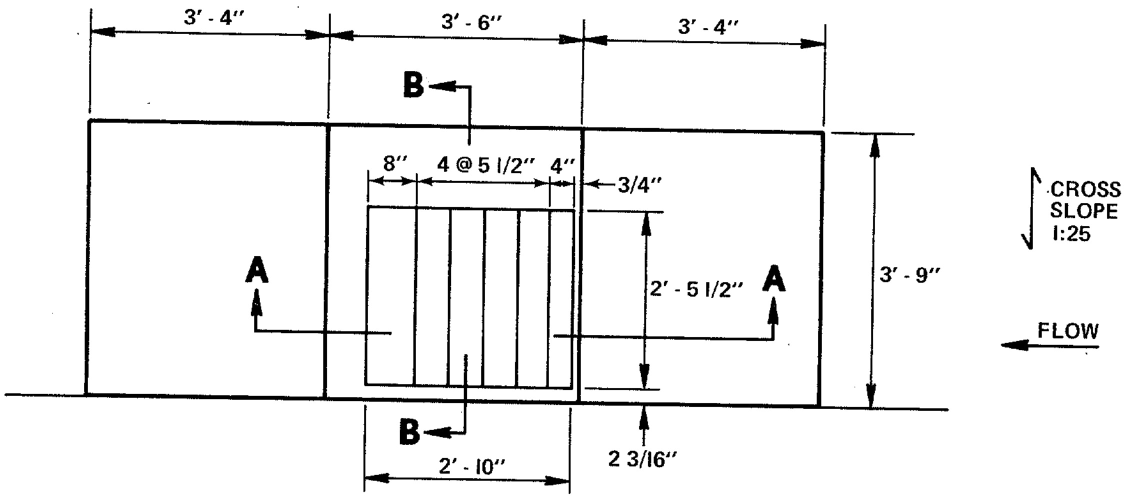


Figure 5. 45° Tilted Transverse - Bar Grate TB 45-3



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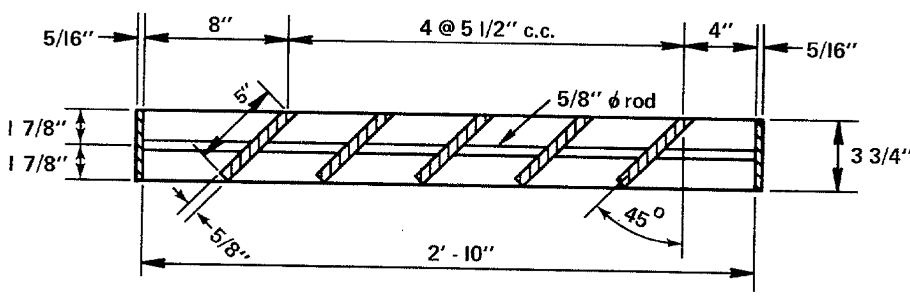
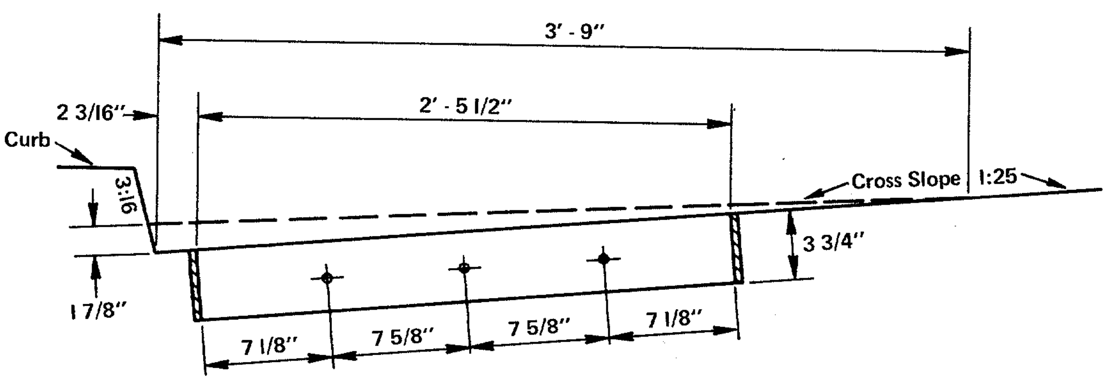
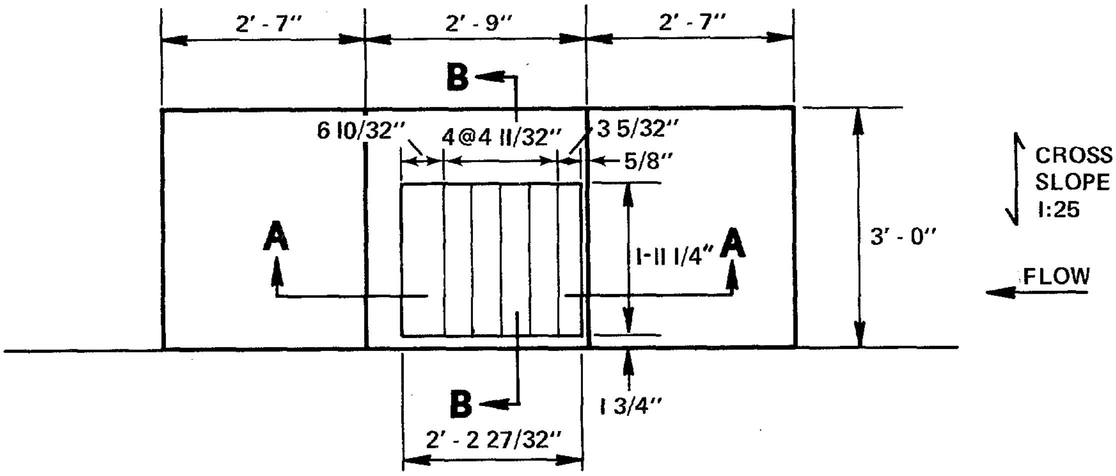


SECTION A-A



SECTION B-B

Figure 6. 45° Tilted Transverse - Bar Grate TB45-5



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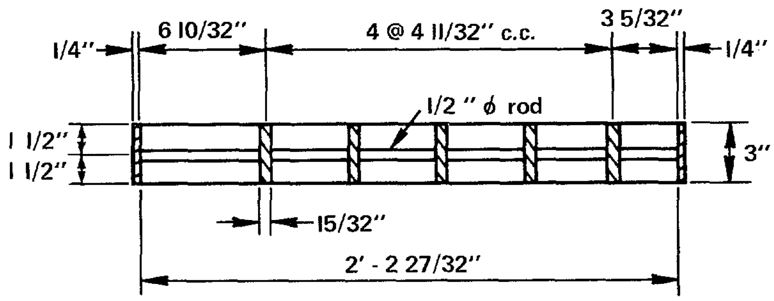

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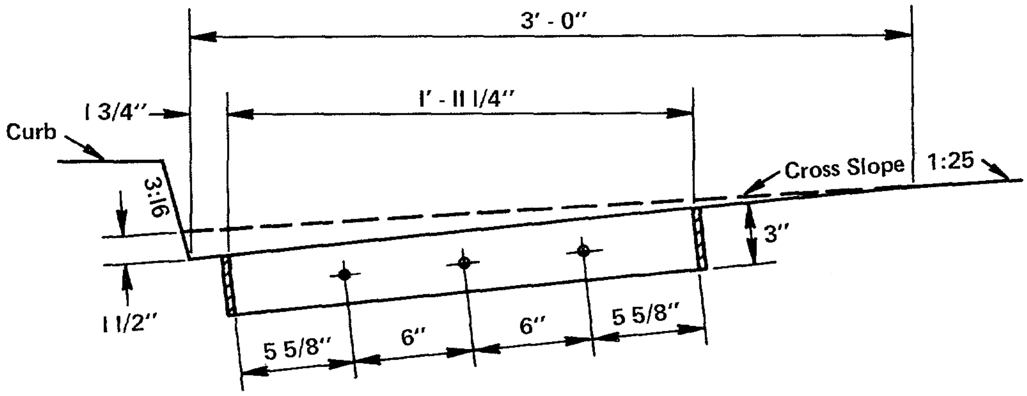


SECTION B-B

Figure 7. Vertical Transverse - Bar Grate TBV-3

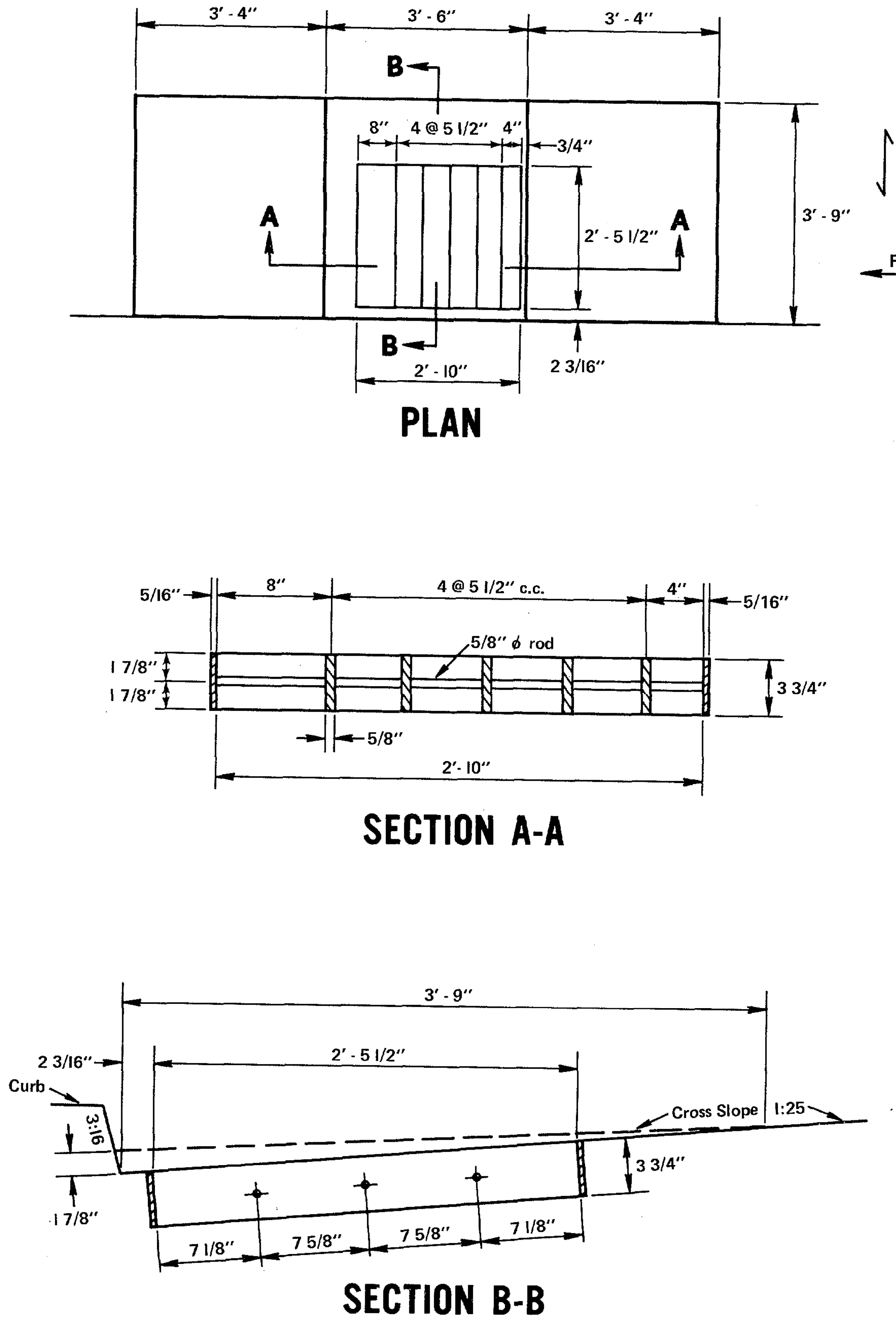


Figure 8. Vertical Transverse - Bar Grate TBV-5

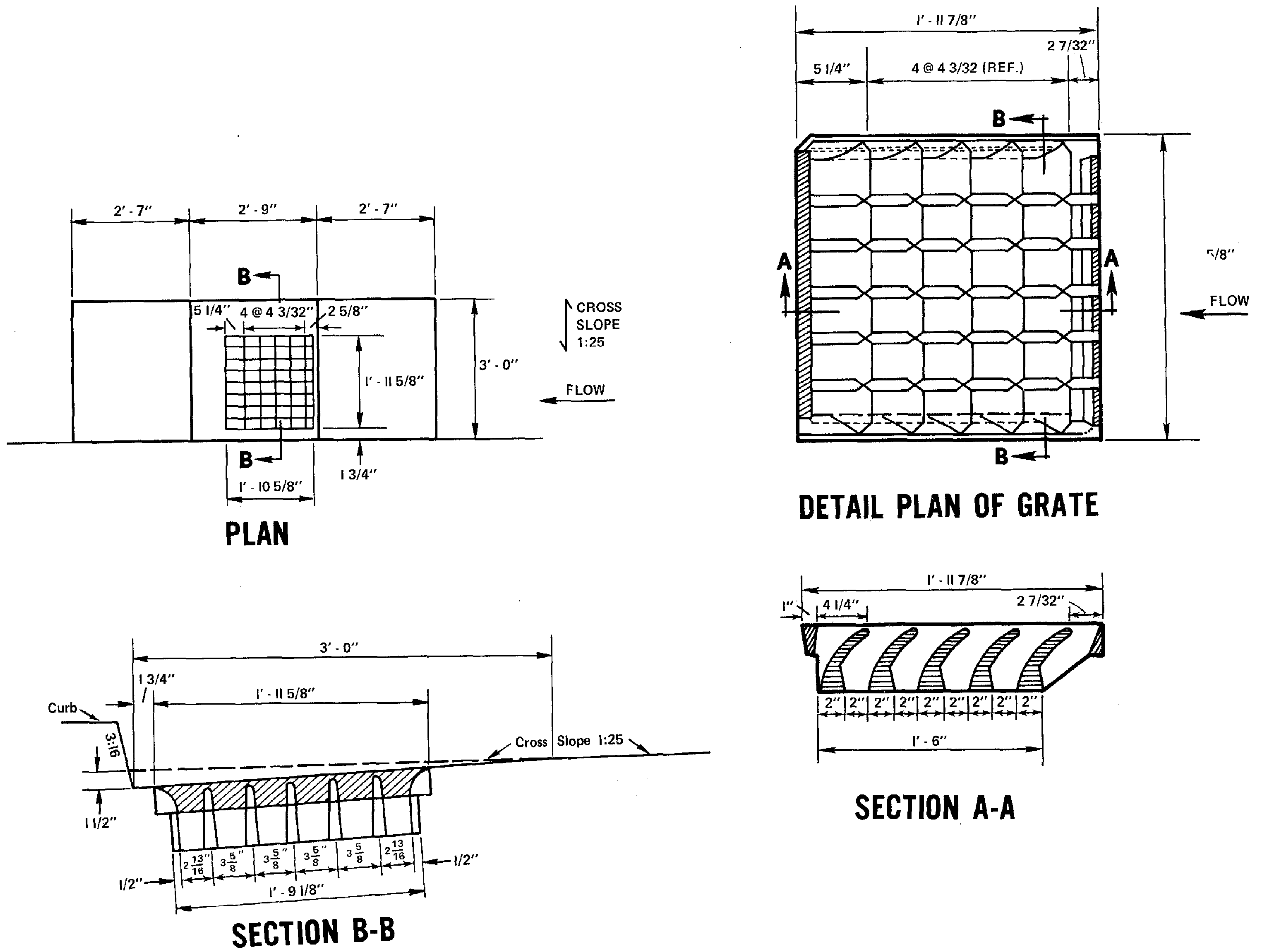


FIGURE 9. MASSACHUSETTS CASCADE GRATE (MASS)

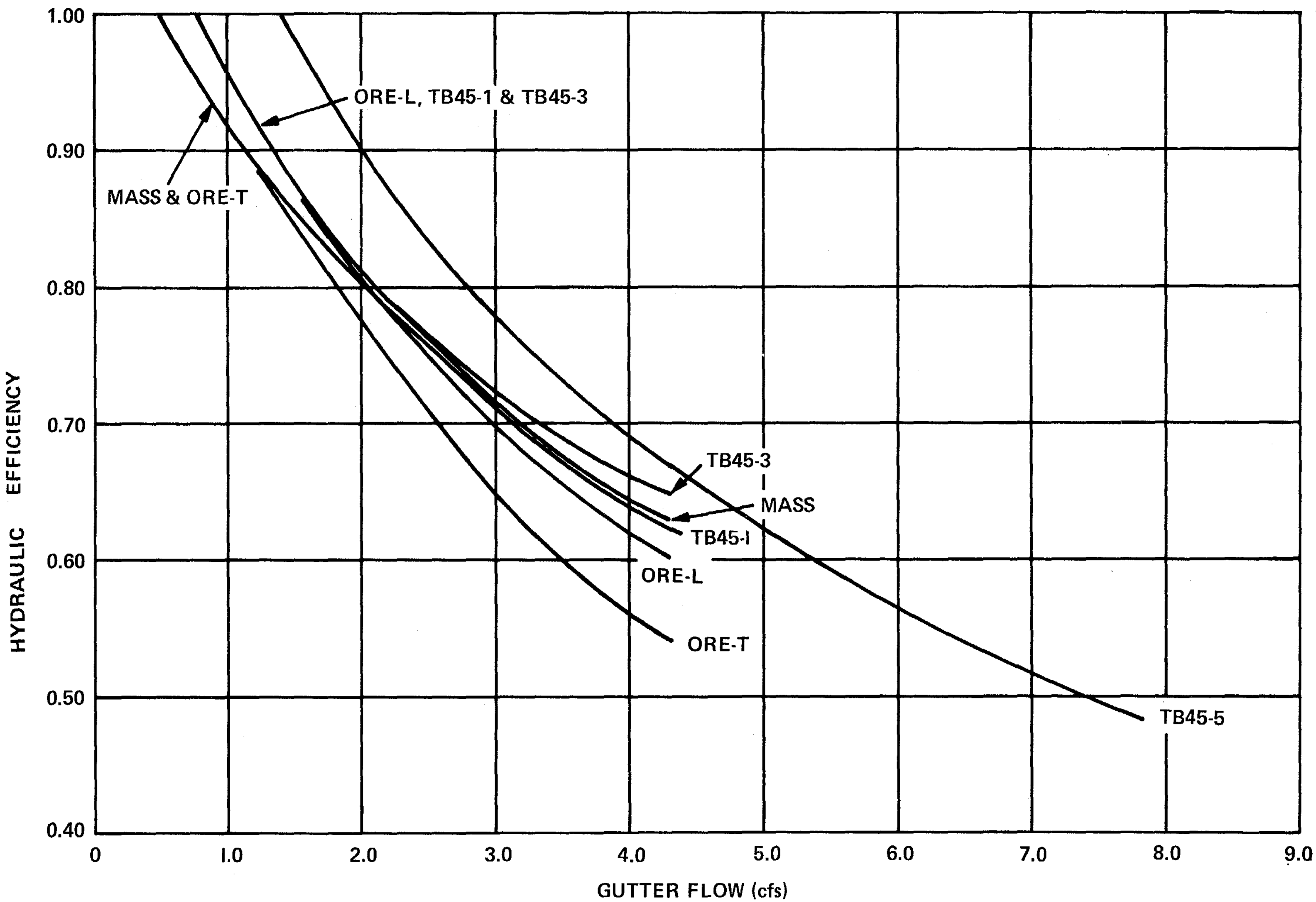


Figure 10. Grate Efficiency Curves for Slope 0.005

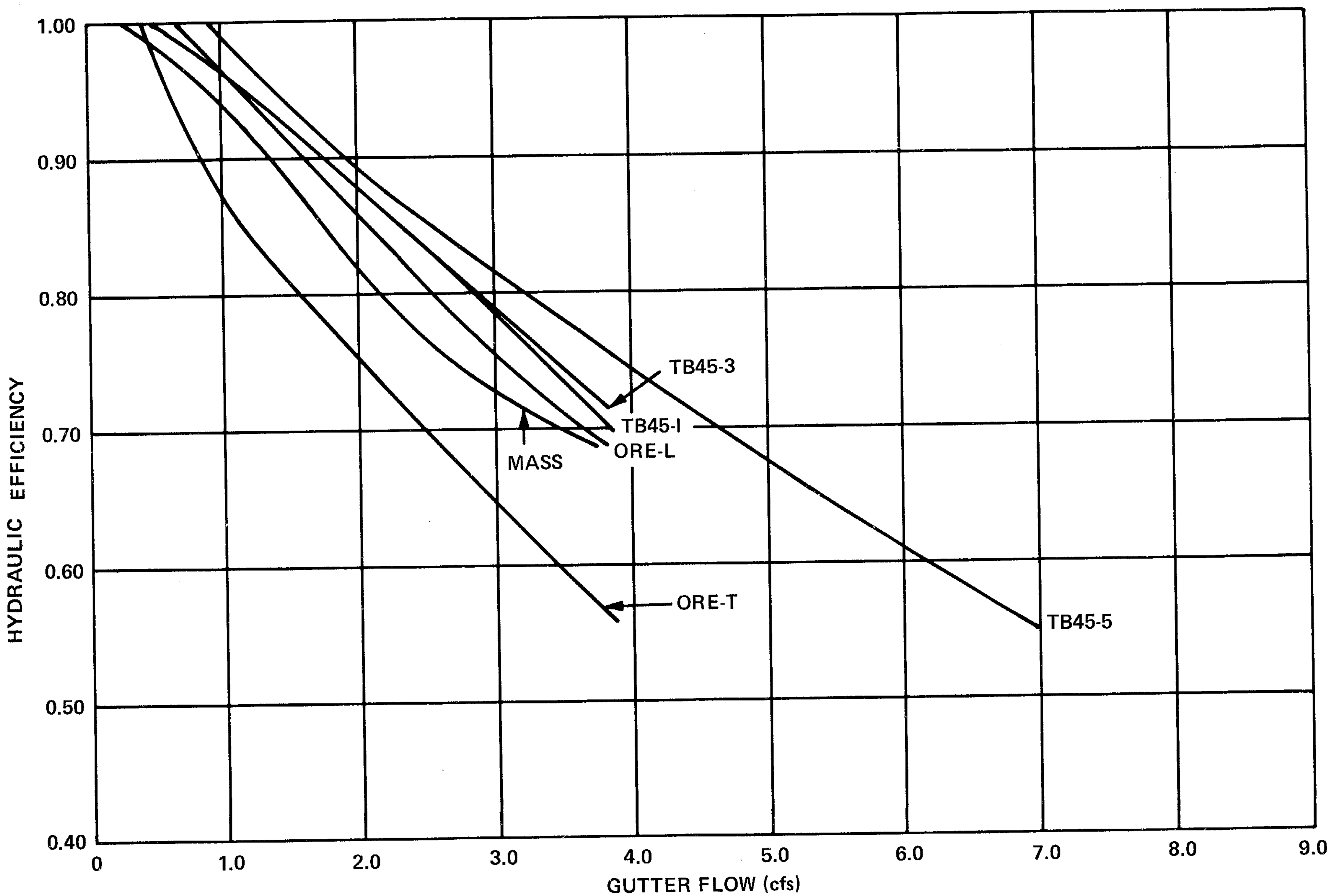


Figure 11. Grate Efficiency Curves for Slope 0.010

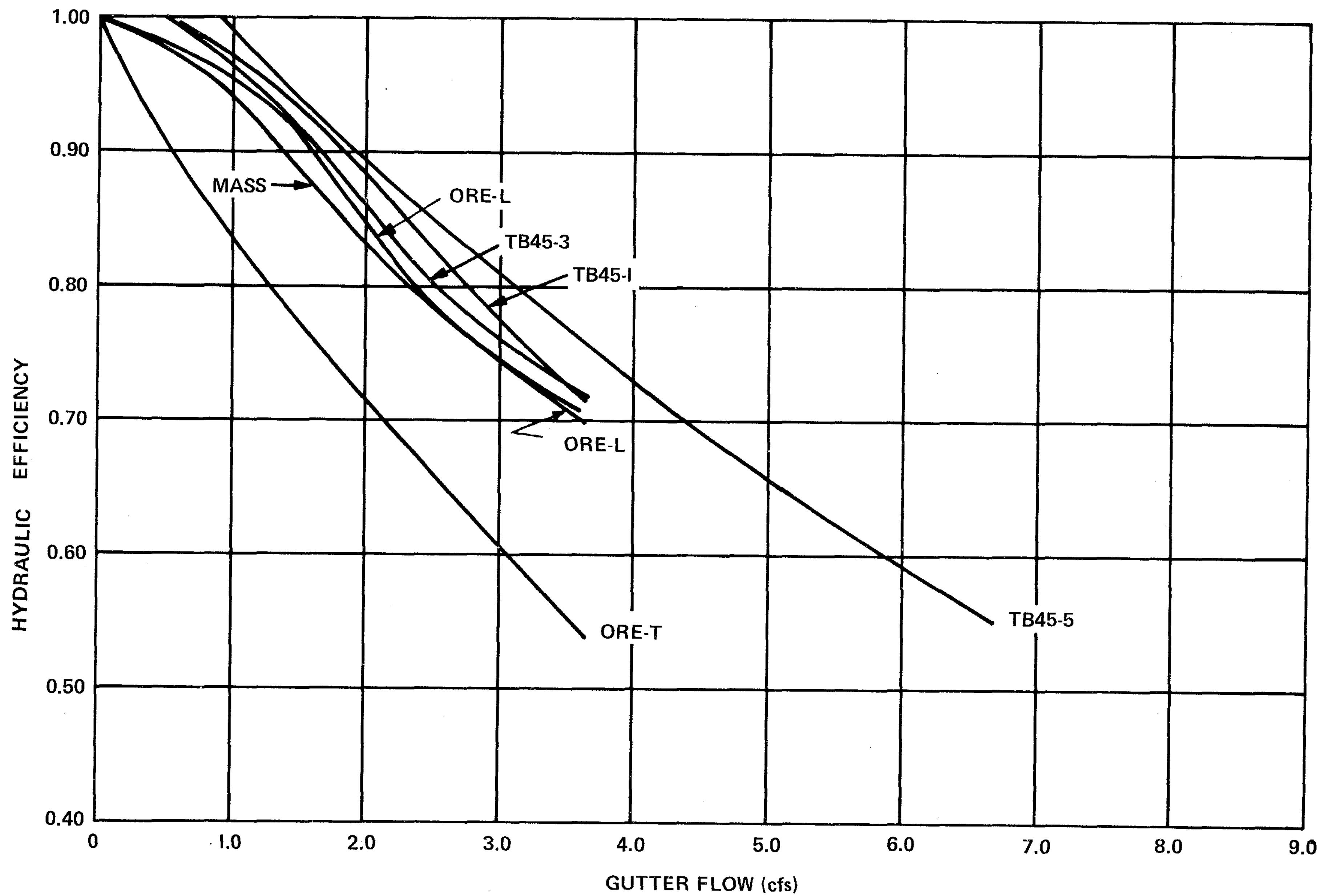


Figure 12. Grate Efficiency Curves for Slope 0.028

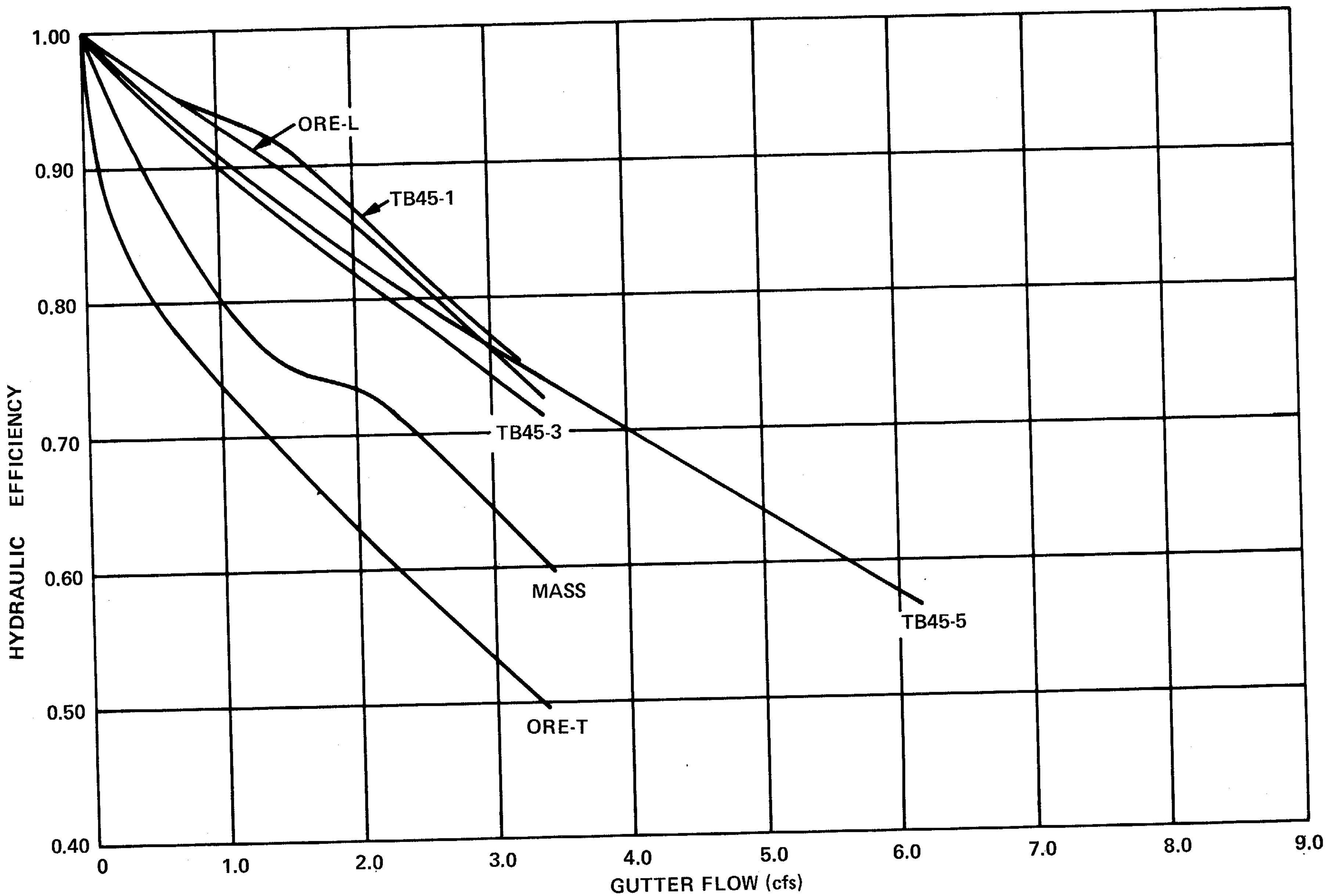


Figure 13. Grate Efficiency Curves for Slope 0.054

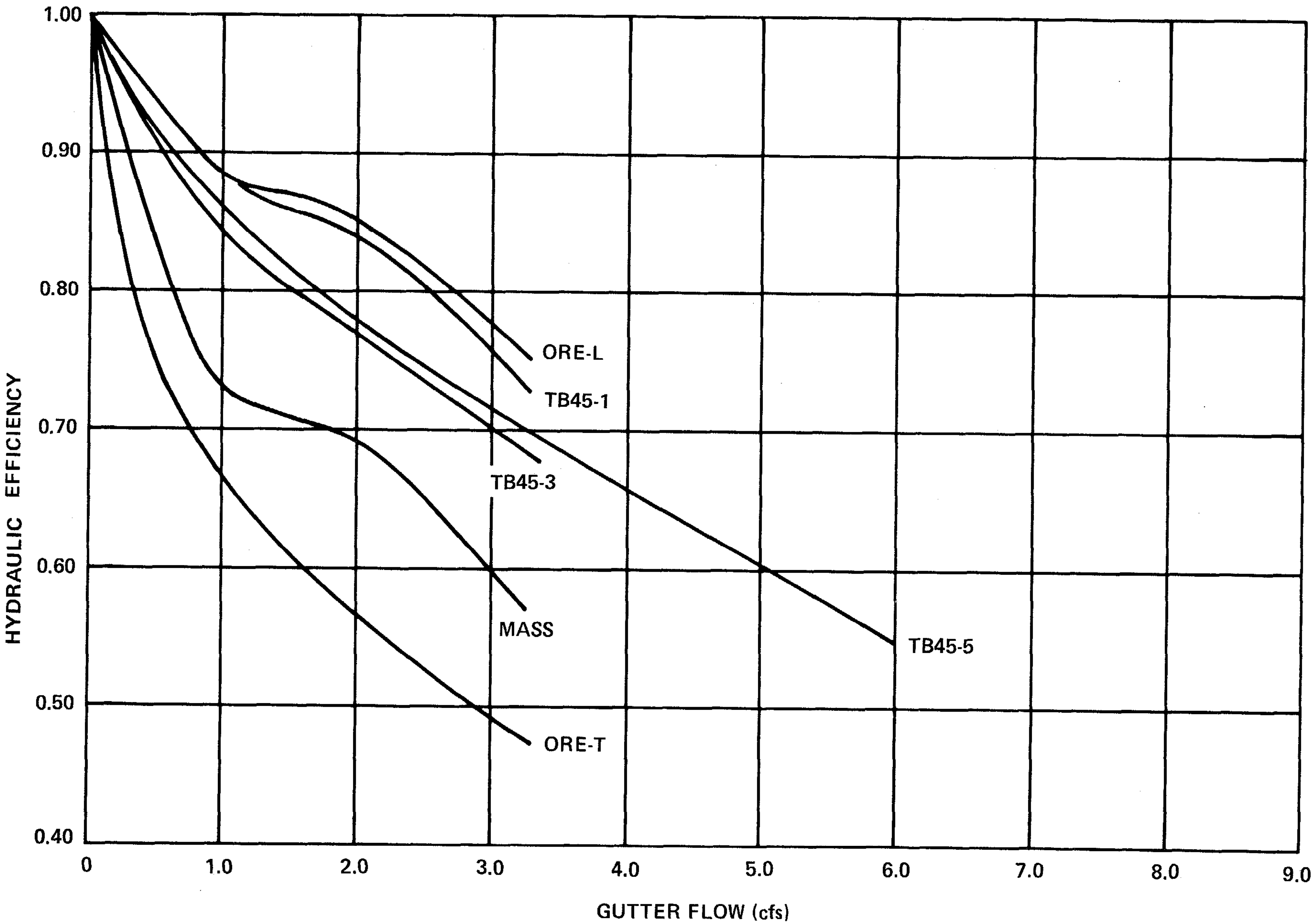


Figure 14. Grate Efficiency Curves for Slope 0.075

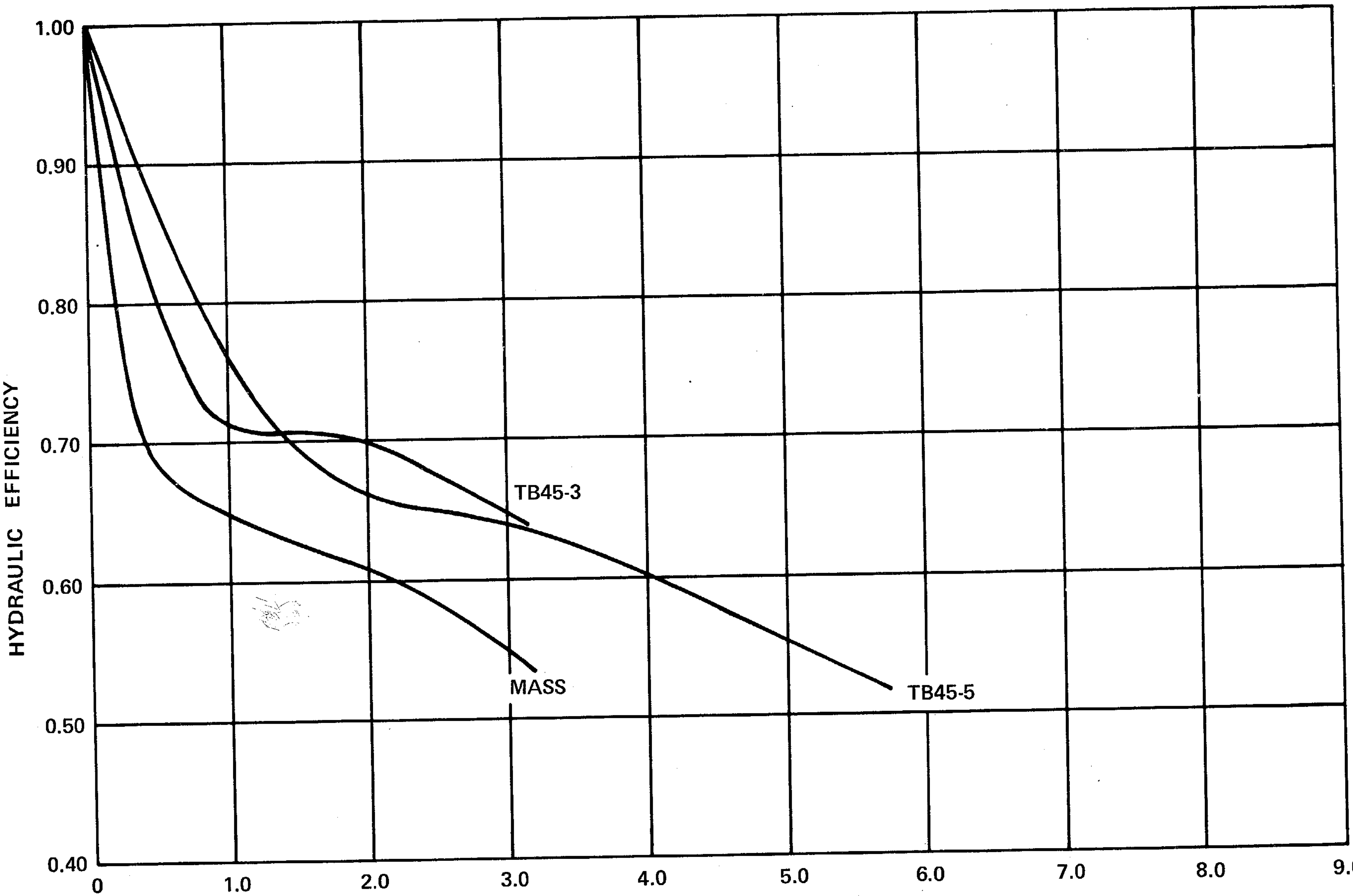


Figure 15. Grate Efficiency Curves for Slope 0.130

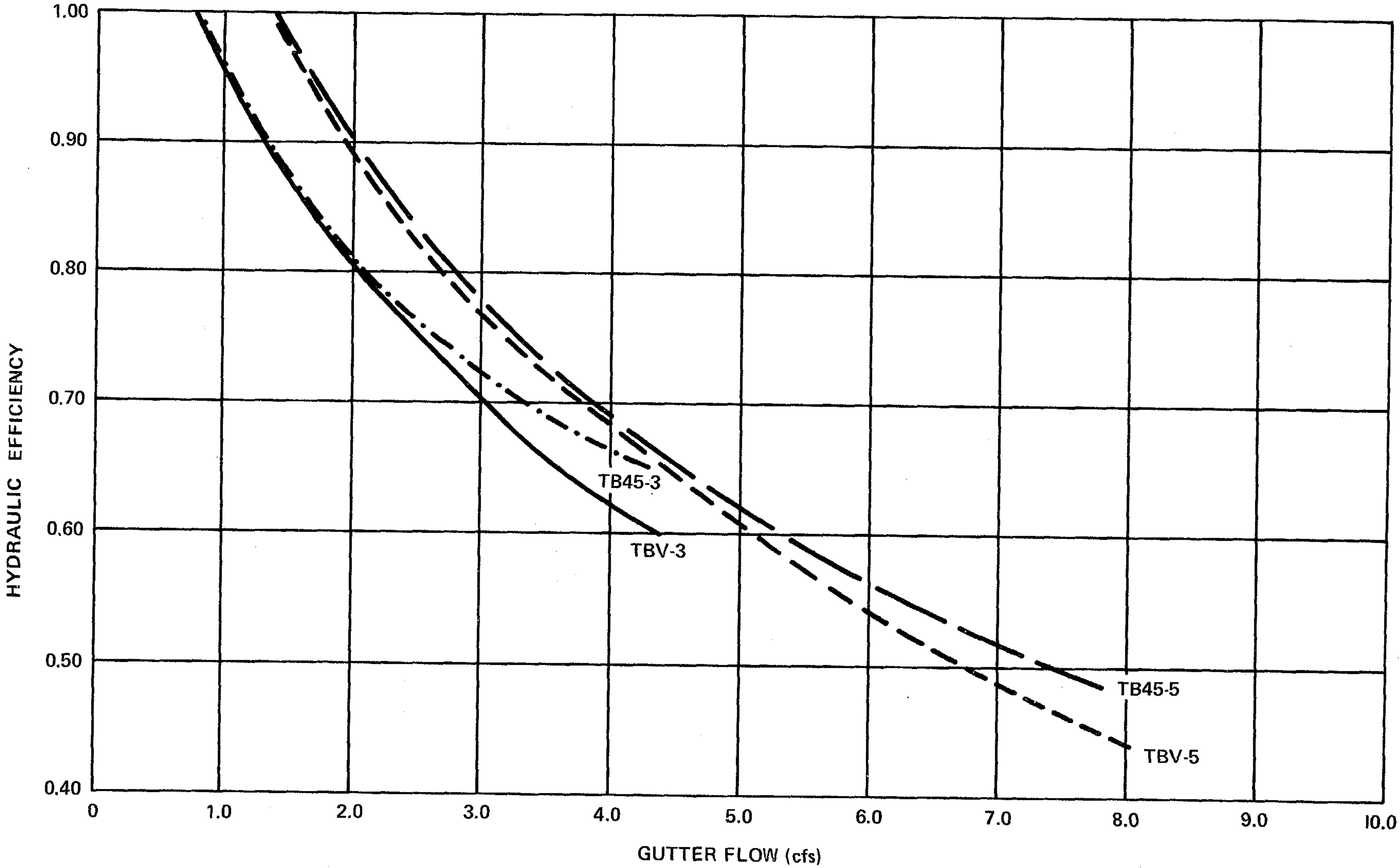


Figure 16. Comparison of Grate Efficiency Curves for Vertical and Tilted Bar Designs for Slope 0.005

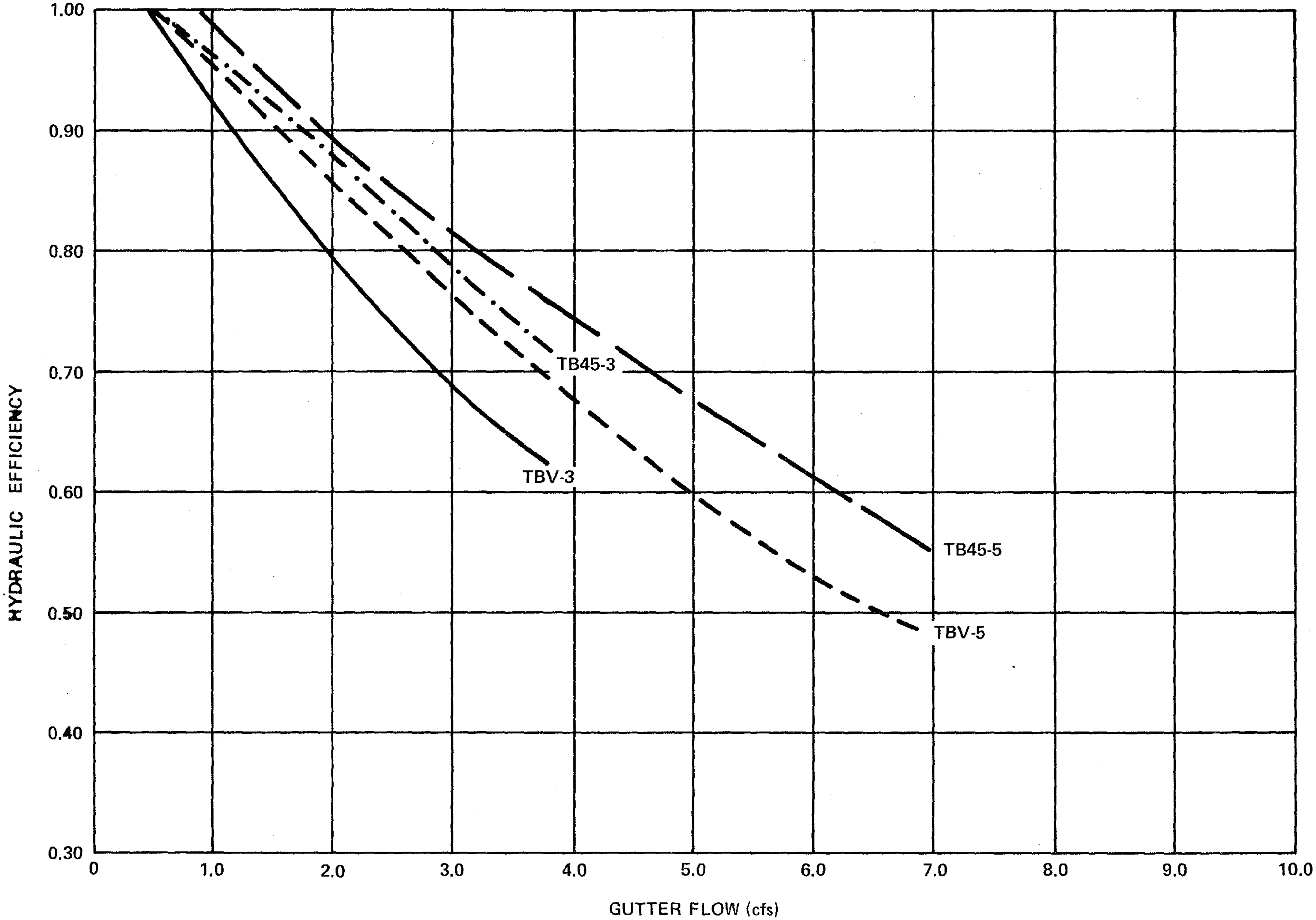


Figure 17. Comparison of Grate Efficiency Curves for Vertical and Tilted Bar Designs for Slope 0.010

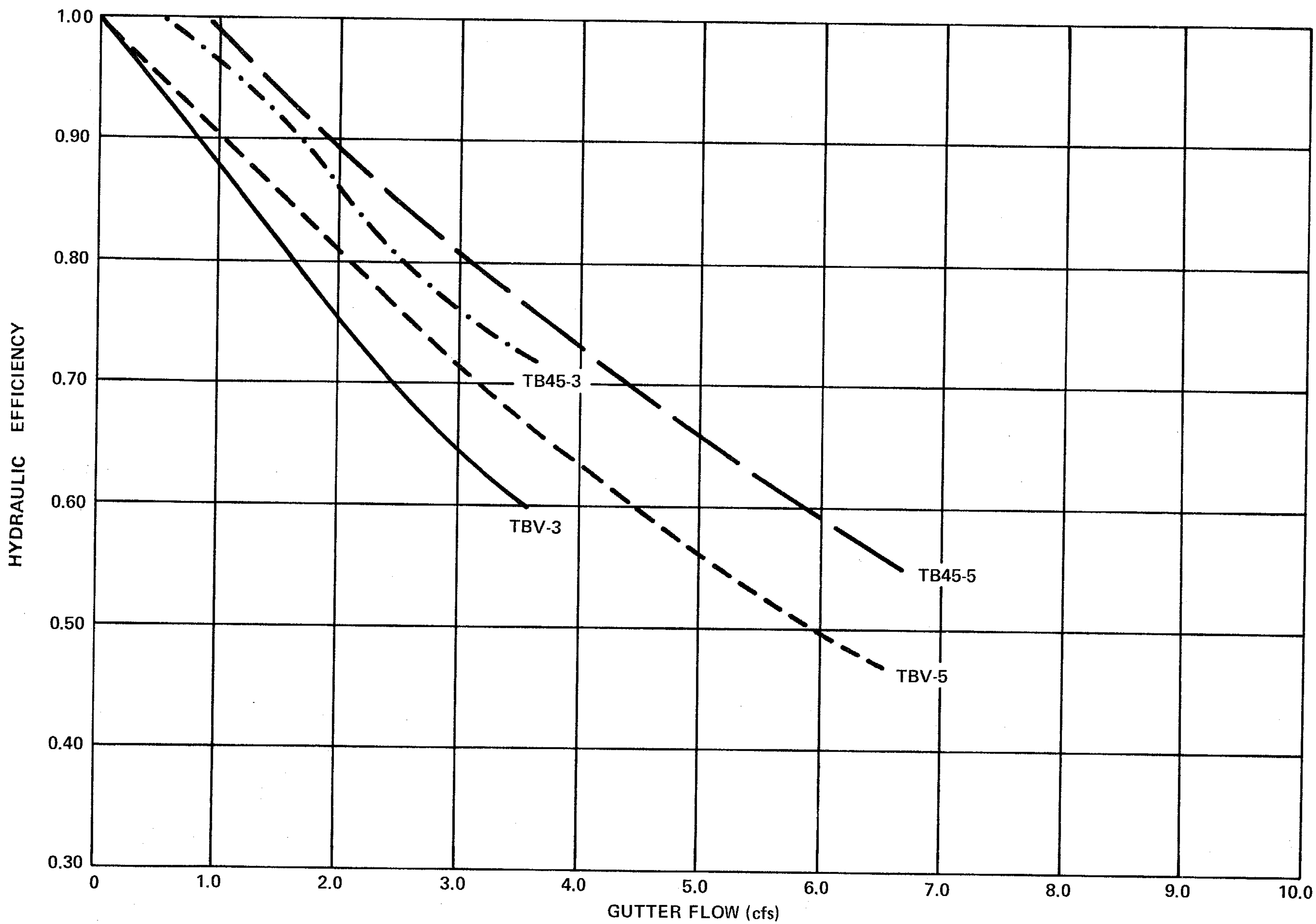


Figure 18. Comparison of Grate Efficiency Curves for Vertical and Tilted Bar Designs for Slope 0.028

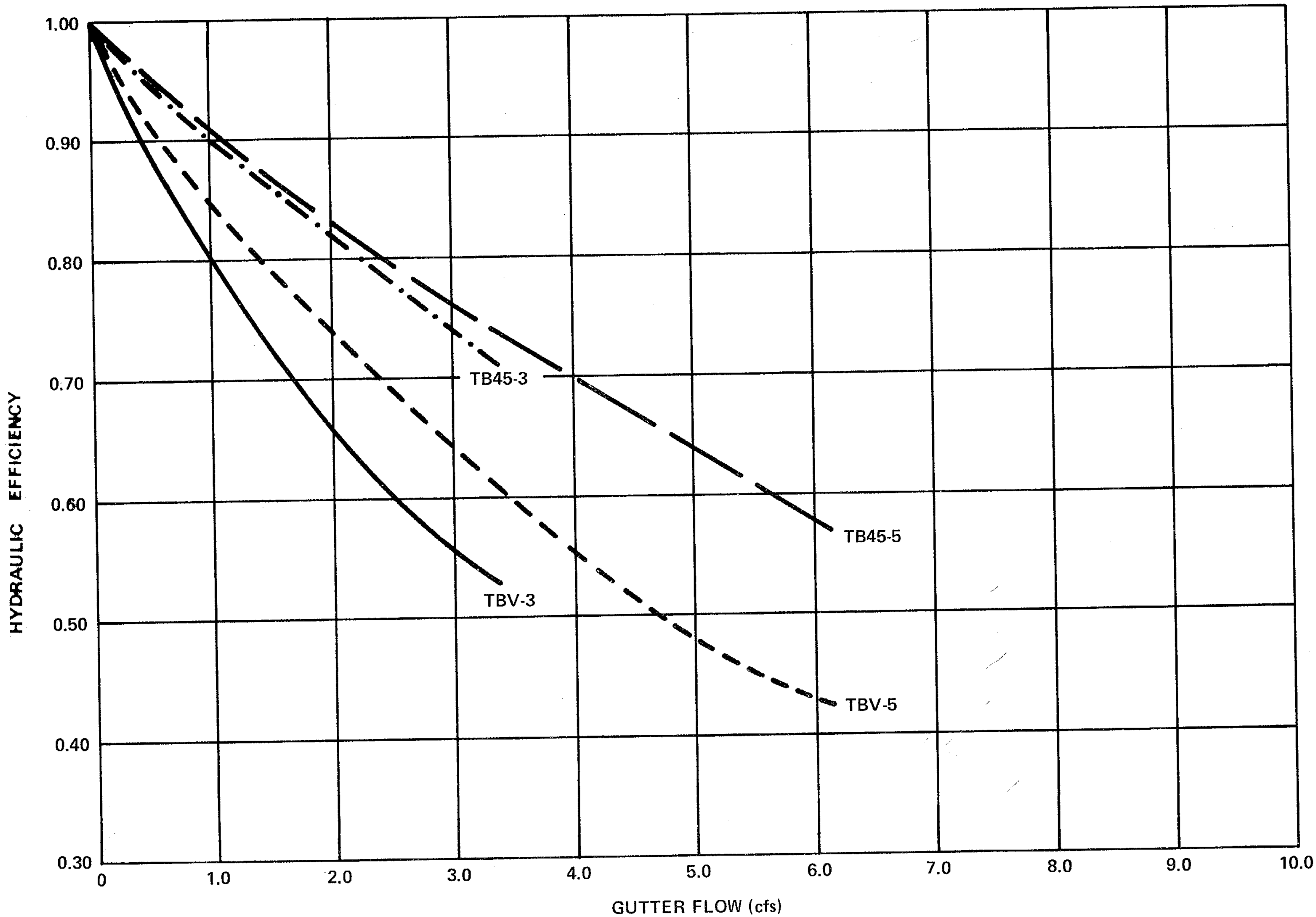


Figure 19. Comparison of Grate Efficiency Curves for Vertical and Tilted Bar Designs for Slope 0.054

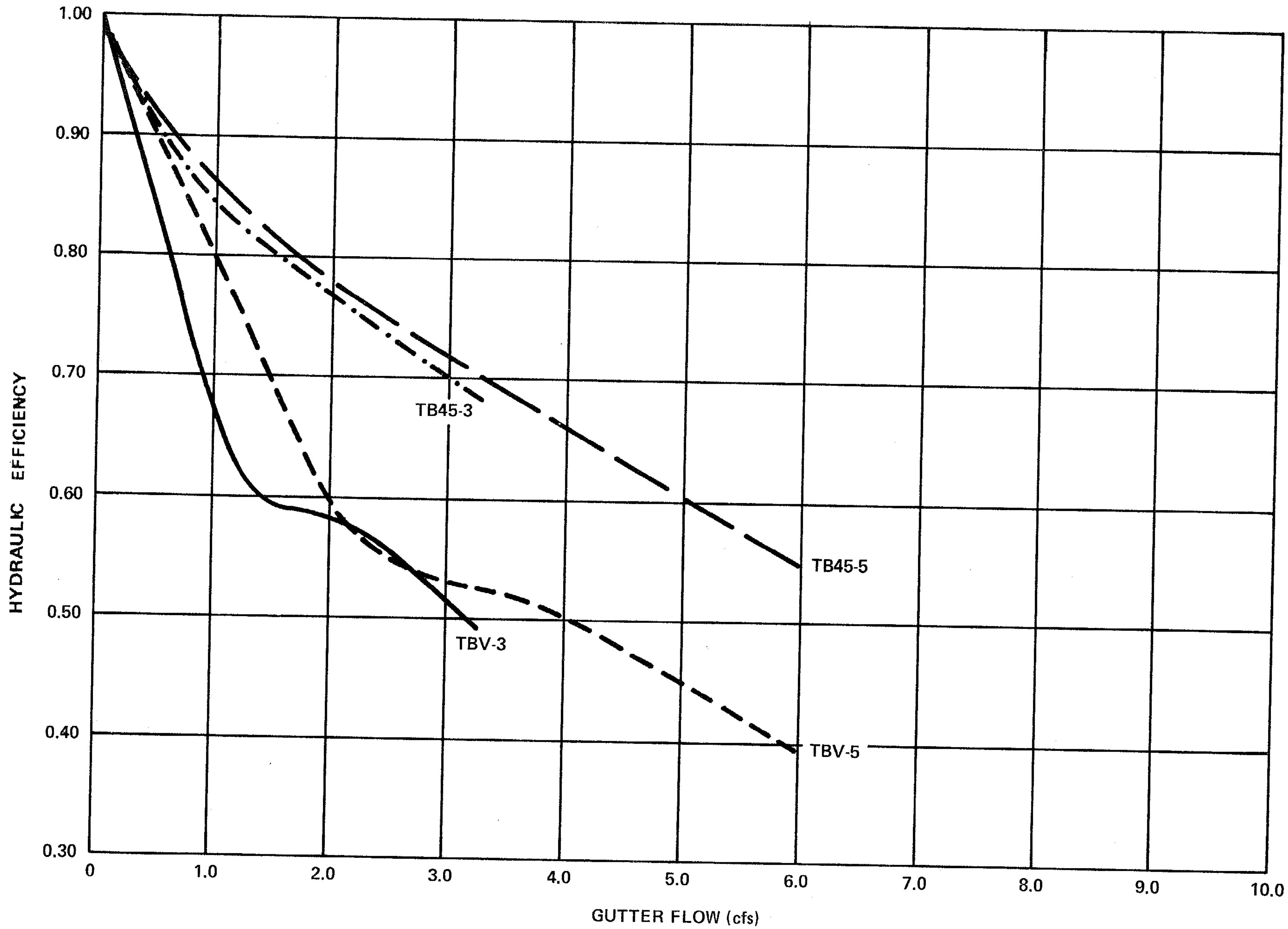


Figure 20. Comparison of Grate Efficiency Curves for Vertical and Tilted Bar Designs for Slope 0.075

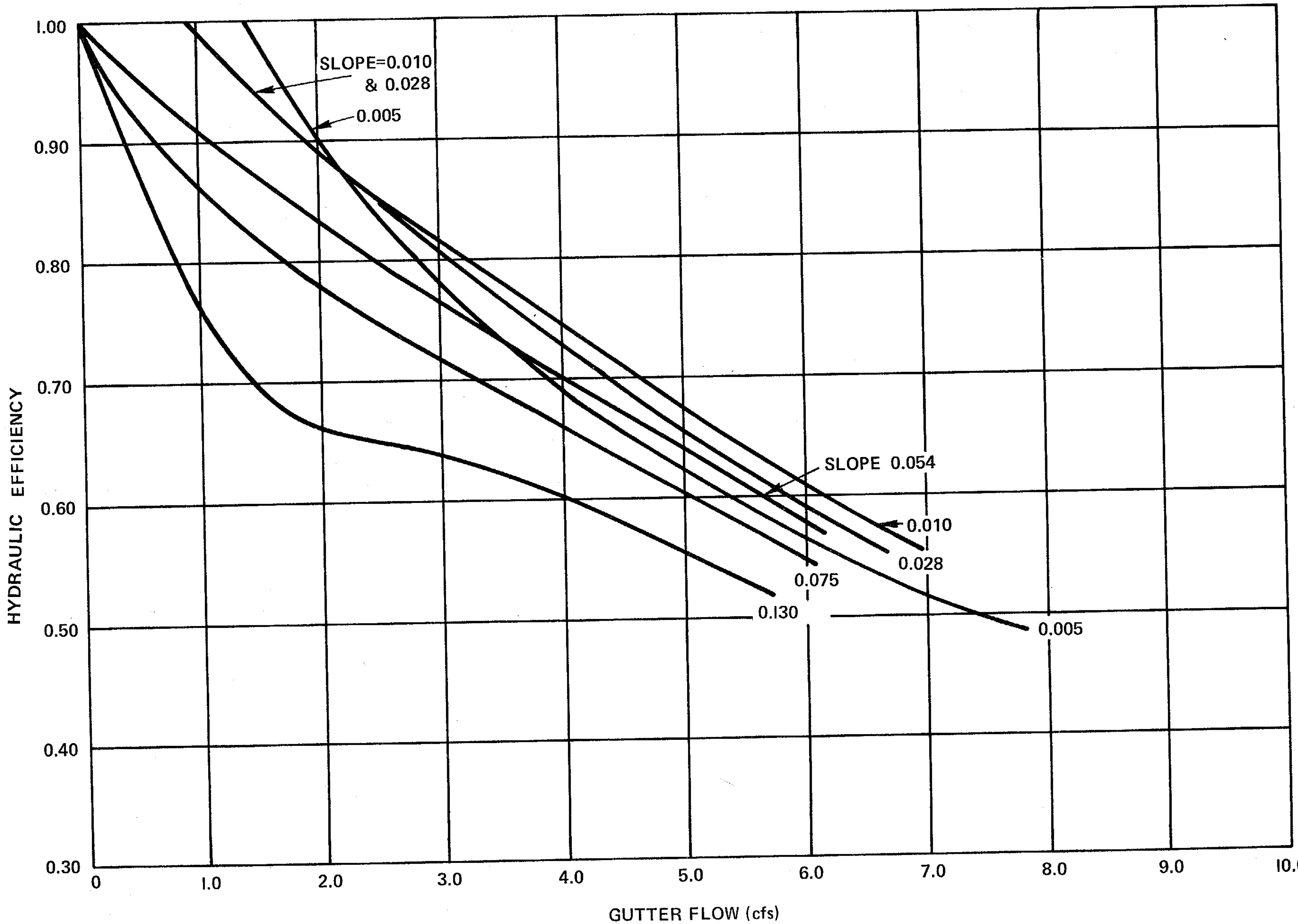


Figure 21. Grate Efficiency Curves for Grate TB45-5 at Various Slopes

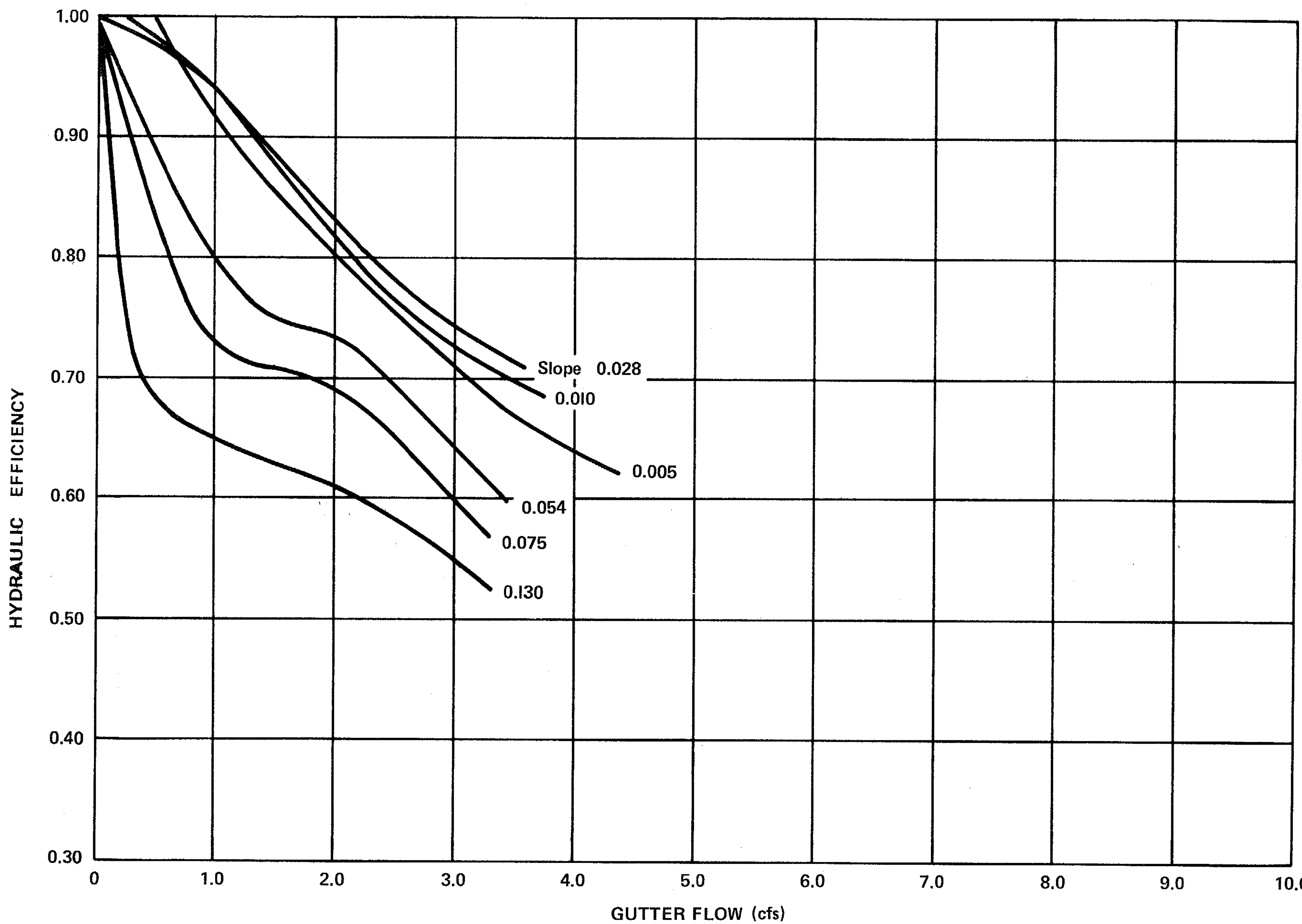


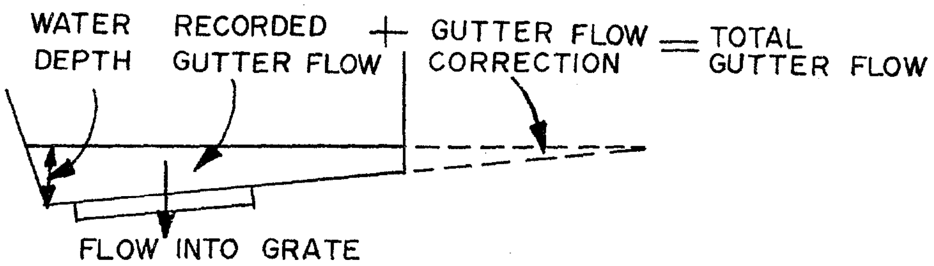
Figure 22. Grate Efficiency Curves for Mass. Cascade Grate (MASS) at Various Slopes

APPENDIX A:

TABULATED TEST RESULTS

TEST RESULTS

GRATE	SLOPE	RECORDED GUTTER FLOW CFS	WATER DEPTH FT	FLOW INTO GRATE CFS	GUTTER FLOW CORRECTION CFS	TOTAL GUTTER FLOW CFS	HYDRAULIC EFFICIENCY %
ORE-L	0.50	1.776	0.259	1.748	0.489	2.265	77.15
ORE-L	0.50	1.980	0.270	1.922	0.600	2.580	74.49
ORE-L	0.50	2.194	0.289	2.099	0.793	2.987	70.26
ORE-L	0.50	2.407	0.304	2.256	0.976	3.383	66.68
ORE-L	0.50	2.665	0.321	2.434	1.207	3.872	62.84
ORE-L	0.50	2.926	0.326	2.591	1.369	4.295	60.33
ORE-L	1.00	0.743	0.133	0.741	0.005	0.748	99.11
ORE-L	1.00	1.020	0.157	1.013	0.034	1.054	96.03
ORE-L	1.00	1.472	0.192	1.454	0.150	1.622	89.67
ORE-L	1.00	1.980	0.217	1.901	0.320	2.300	82.64
ORE-L	1.00	2.407	0.238	2.227	0.525	2.932	75.98
ORE-L	1.00	2.926	0.269	2.623	0.884	3.810	68.85
ORE-L	2.80	0.743	0.126	0.719	0.002	0.745	96.56
ORE-L	2.80	1.020	0.144	0.990	0.018	1.038	95.35
ORE-L	2.80	1.472	0.179	1.430	0.110	1.582	90.41
ORE-L	2.80	1.980	0.206	1.831	0.271	2.251	81.35
ORE-L	2.80	2.407	0.222	2.143	0.420	2.827	75.82
ORE-L	2.80	2.926	0.245	2.532	0.689	3.615	70.04
ORE-L	5.40	0.743	0.126	0.705	0.002	0.745	94.66
ORE-L	5.40	1.020	0.166	0.964	0.059	1.079	89.34
ORE-L	5.40	1.472	0.162	1.375	0.063	1.535	89.55
ORE-L	5.40	1.980	0.183	1.799	0.165	2.145	83.87
ORE-L	5.40	2.407	0.195	2.130	0.263	2.670	79.77
ORE-L	5.40	2.926	0.215	2.451	0.461	3.387	72.37
ORE-L	7.50	0.743	0.103	0.676	0.0	0.743	90.93
ORE-L	7.50	1.020	0.142	0.910	0.016	1.036	87.86
ORE-L	7.50	1.472	0.146	1.306	0.028	1.500	87.08
ORE-L	7.50	1.980	0.170	1.770	0.115	2.095	84.50
ORE-L	7.50	2.407	0.185	2.109	0.208	2.615	80.64
ORE-L	7.50	2.926	0.198	2.461	0.342	3.268	75.29



DEFINITIVE SKETCH FOR TABLE HEADINGS

TEST RESULTS (CONTINUED)

GRATE	SLOPE	RECORDED GUTTER FLOW	WATER DEPTH	FLOW INTO GRATE	GUTTER FLOW CORRECTION	TOTAL GUTTER FLOW	HYDRAULIC EFFICIENCY
		CFS	FT	CFS	CFS	CFS	%
ORE-T	0.50	1.020	0.263	1.018	0.295	1.315	77.42
ORE-T	0.50	1.472	0.233	1.435	0.295	1.767	81.22
ORE-T	0.50	1.776	0.259	1.674	0.489	2.265	73.91
ORE-T	0.50	1.980	0.269	1.803	0.595	2.575	70.01
ORE-T	0.50	2.407	0.308	2.054	1.004	3.411	60.24
ORE-T	0.50	2.926	0.327	2.347	1.383	4.309	54.46
ORE-T	1.00	0.510	0.131	0.498	0.003	0.513	97.21
ORE-T	1.00	0.743	0.128	0.686	0.002	0.745	92.02
ORE-T	1.00	1.020	0.157	0.908	0.035	1.055	86.06
ORE-T	1.00	1.472	0.193	1.292	0.154	1.626	79.49
ORE-T	1.00	1.980	0.216	1.652	0.314	2.294	72.03
ORE-T	1.00	2.926	0.278	2.164	0.953	3.879	55.78
ORE-T	2.80	0.276	0.087	0.261	0.0	0.276	94.71
ORE-T	2.80	0.743	0.127	0.643	0.002	0.745	86.30
ORE-T	2.80	1.020	0.144	0.862	0.018	1.038	83.01
ORE-T	2.80	1.472	0.177	1.225	0.107	1.579	77.59
ORE-T	2.80	1.980	0.206	1.537	0.270	2.250	68.31
ORE-T	2.80	2.926	0.247	1.958	0.713	3.639	53.79
ORE-T	5.40	0.276	0.076	0.232	0.0	0.276	83.91
ORE-T	5.40	0.743	0.132	0.581	0.004	0.747	77.74
ORE-T	5.40	1.020	0.166	0.774	0.057	1.077	71.88
ORE-T	5.40	1.472	0.159	1.072	0.056	1.528	70.16
ORE-T	5.40	1.980	0.184	1.305	0.169	2.149	60.71
ORE-T	5.40	2.926	0.214	1.677	0.455	3.381	49.59
ORE-T	7.50	0.276	0.072	0.228	0.0	0.276	82.61
ORE-T	7.50	0.743	0.106	0.520	0.0	0.743	70.05
ORE-T	7.50	1.020	0.144	0.694	0.017	1.037	66.91
ORE-T	7.50	1.472	0.145	0.904	0.027	1.499	60.29
ORE-T	7.50	1.980	0.173	1.175	0.125	2.105	55.83
ORE-T	7.50	2.926	0.203	1.561	0.378	3.304	47.25

TEST RESULTS (CONTINUED)

GRATE	SLOPE	RECORDED GUTTER FLOW CFS	WATER DEPTH FT	FLOW INTO GRATE CFS	GUTTER FLOW CORRECTION CFS	TOTAL GUTTER FLOW CFS	HYDRAULIC EFFICIENCY %
TB45-1	0.50	1.776	0.258	1.771	0.483	2.259	78.40
TB45-1	0.50	1.980	0.271	1.956	0.609	2.589	75.55
TB45-1	0.50	2.194	0.290	2.143	0.801	2.995	71.54
TB45-1	0.50	2.407	0.306	2.313	0.987	3.394	68.14
TB45-1	0.50	2.665	0.318	2.517	1.188	3.853	65.33
TB45-1	0.50	2.926	0.326	2.732	1.369	4.295	63.61
TB45-1	1.00	1.776	0.206	1.775	0.239	2.015	88.08
TB45-1	1.00	1.980	0.217	1.961	0.319	2.299	85.31
TB45-1	1.00	2.201	0.228	2.156	0.419	2.620	82.30
TB45-1	1.00	2.407	0.241	2.323	0.539	2.946	78.84
TB45-1	1.00	2.680	0.259	2.525	0.737	3.417	73.91
TB45-1	1.00	2.926	0.278	2.719	0.950	3.876	70.14
TB45-1	2.80	1.776	0.194	1.749	0.191	1.967	88.94
TB45-1	2.80	1.980	0.205	1.917	0.263	2.243	85.46
TB45-1	2.80	2.194	0.213	2.088	0.339	2.533	82.44
TB45-1	2.80	2.407	0.222	2.247	0.423	2.830	79.40
TB45-1	2.80	2.665	0.232	2.421	0.541	3.206	75.51
TB45-1	2.80	2.926	0.245	2.595	0.696	3.622	71.64
TB45-1	5.40	1.020	0.164	1.000	0.054	1.074	93.10
TB45-1	5.40	1.472	0.159	1.405	0.057	1.529	91.91
TB45-1	5.40	1.942	0.182	1.797	0.160	2.103	85.48
TB45-1	5.40	2.400	0.195	2.144	0.266	2.666	80.42
TB45-1	5.40	2.665	0.203	2.320	0.343	3.008	77.11
TB45-1	5.40	2.926	0.215	2.491	0.462	3.388	73.54
TB45-1	7.50	0.743	0.108	0.710	0.0	0.743	95.53
TB45-1	7.50	1.472	0.149	1.292	0.033	1.505	85.84
TB45-1	7.50	1.980	0.165	1.733	0.096	2.076	83.48
TB45-1	7.50	2.407	0.184	2.072	0.203	2.610	79.39
TB45-1	7.50	2.665	0.191	2.241	0.268	2.933	76.42
TB45-1	7.50	2.926	0.201	2.396	0.361	3.287	72.91

TEST RESULTS (CONTINUED)

GRATE	SLOPE	RECORDED GUTTER FLOW CFS	WATER DEPTH FT	FLOW INTO GRATE CFS	GUTTER FLOW CORRECTION CFS	TOTAL GUTTER FLOW CFS	HYDRAULIC EFFICIENCY %
TB45-3	0.50	1.776	0.258	1.772	0.479	2.255	78.58
TB45-3	0.50	1.980	0.270	1.962	0.598	2.578	76.08
TB45-3	0.50	2.194	0.288	2.157	0.784	2.978	72.45
TB45-3	0.50	2.407	0.302	2.348	0.967	3.374	69.60
TB45-3	0.50	2.665	0.316	2.566	1.174	3.839	66.84
TB45-3	0.50	2.926	0.326	2.788	1.372	4.298	64.87
TB45-3	1.00	1.244	0.178	1.238	0.090	1.334	92.83
TB45-3	1.00	1.776	0.206	1.759	0.238	2.014	87.36
TB45-3	1.00	1.980	0.216	1.945	0.314	2.294	84.78
TB45-3	1.00	2.407	0.237	2.317	0.513	2.920	79.35
TB45-3	1.00	2.665	0.255	2.525	0.701	3.366	75.01
TB45-3	1.00	2.926	0.272	2.737	0.906	3.832	71.43
TB45-3	2.80	1.020	0.146	1.003	0.019	1.039	96.45
TB45-3	2.80	1.245	0.169	1.224	0.069	1.314	93.19
TB45-3	2.80	1.474	0.182	1.445	0.120	1.594	90.65
TB45-3	2.80	1.776	0.195	1.713	0.197	1.973	86.81
TB45-3	2.80	1.980	0.208	1.871	0.279	2.259	82.82
TB45-3	2.80	2.400	0.223	2.187	0.432	2.832	77.25
TB45-3	2.80	2.940	0.247	2.614	0.715	3.655	71.51
TB45-3	5.40	1.020	0.167	0.960	0.062	1.082	88.72
TB45-3	5.40	1.472	0.161	1.324	0.061	1.533	86.38
TB45-3	5.40	1.776	0.173	1.568	0.111	1.887	83.06
TB45-3	5.40	1.980	0.182	1.734	0.162	2.142	80.96
TB45-3	5.40	2.407	0.199	2.069	0.288	2.695	76.78
TB45-3	5.40	2.926	0.215	2.410	0.464	3.390	71.09
TB45-3	7.50	1.020	0.140	0.864	0.013	1.033	83.62
TB45-3	7.50	1.244	0.139	1.040	0.014	1.258	82.61
TB45-3	7.50	1.472	0.149	1.202	0.034	1.506	79.82
TB45-3	7.50	1.980	0.165	1.600	0.096	2.076	77.07
TB45-3	7.50	2.407	0.184	1.919	0.205	2.612	73.50
TB45-3	7.50	2.926	0.201	2.230	0.364	3.290	67.78
TB45-3	13.00	0.510	0.092	0.406	0.0	0.510	79.61
TB45-3	13.00	1.020	0.109	0.726	0.0	1.020	71.14
TB45-3	13.00	1.472	0.134	1.048	0.011	1.483	70.70
TB45-3	13.00	1.980	0.144	1.409	0.034	2.014	69.96
TB45-3	13.00	2.407	0.162	1.692	0.103	2.510	67.39
TB45-3	13.00	2.926	0.179	2.007	0.220	3.146	63.78

TEST RESULTS (CONTINUED)

GRATE	SLOPE	RECORDED GUTTER FLOW CFS	WATER DEPTH FT	FLOW INTO GRATE CFS	GUTTER FLOW CORRECTION CFS	TOTAL GUTTER FLOW CFS	HYDRAULIC EFFICIENCY %
MASS	0.50	1.244	0.224	1.244	0.227	1.471	84.56
MASS	0.50	1.472	0.232	1.471	0.295	1.767	83.27
MASS	0.50	1.776	0.254	1.758	0.461	2.237	78.60
MASS	0.50	1.970	0.270	1.929	0.598	2.568	75.09
MASS	0.50	2.194	0.287	2.118	0.784	2.978	71.10
MASS	0.50	2.421	0.302	2.298	0.969	3.390	67.78
MASS	0.50	2.933	0.332	2.718	1.431	4.364	62.27
MASS	1.00	1.244	0.175	1.197	0.081	1.325	90.33
MASS	1.00	1.472	0.192	1.397	0.151	1.623	86.12
MASS	1.00	1.776	0.204	1.642	0.232	2.008	81.74
MASS	1.00	1.980	0.215	1.792	0.310	2.290	78.26
MASS	1.00	2.407	0.237	2.139	0.513	2.920	73.26
MASS	1.00	2.926	0.261	2.572	0.825	3.751	68.57
MASS	2.80	1.020	0.144	0.972	0.018	1.038	93.65
MASS	2.80	1.244	0.163	1.179	0.056	1.300	90.72
MASS	2.80	1.472	0.179	1.388	0.110	1.582	87.72
MASS	2.80	1.980	0.204	1.807	0.260	2.240	80.66
MASS	2.80	2.407	0.226	2.152	0.452	2.859	75.30
MASS	2.80	2.926	0.241	2.542	0.659	3.585	70.91
MASS	5.40	0.497	0.103	0.442	0.0	0.497	88.98
MASS	5.40	1.020	0.165	0.858	0.057	1.077	79.65
MASS	5.40	1.244	0.179	1.024	0.106	1.350	75.87
MASS	5.40	1.472	0.190	1.216	0.160	1.632	74.51
MASS	5.40	1.980	0.185	1.578	0.173	2.153	73.31
MASS	5.40	2.407	0.202	1.802	0.305	2.712	66.43
MASS	5.40	2.940	0.215	2.076	0.463	3.403	61.00
MASS	7.50	0.510	0.093	0.425	0.0	0.510	83.33
MASS	7.50	1.020	0.139	0.746	0.011	1.031	72.33
MASS	7.50	1.472	0.149	1.068	0.034	1.506	70.89
MASS	7.50	1.980	0.166	1.426	0.099	2.079	68.60
MASS	7.50	2.407	0.184	1.665	0.205	2.612	63.76
MASS	7.50	2.926	0.197	1.861	0.338	3.264	57.02
MASS	13.00	0.514	0.125	0.350	0.002	0.516	67.81
MASS	13.00	1.020	0.113	0.660	0.0	1.020	64.73
MASS	13.00	1.472	0.136	0.932	0.013	1.485	62.72
MASS	13.00	1.970	0.146	1.218	0.037	2.007	60.68
MASS	13.00	2.407	0.166	1.469	0.120	2.527	58.15
MASS	13.00	2.940	0.183	1.695	0.247	3.187	53.19

TEST RESULTS (CONTINUED)

GRATE	SLOPE	RECORDED GUTTER FLOW CFS	WATER DEPTH FT	FLOW INTO GRATE CFS	GUTTER FLOW CORRECTION CFS	TOTAL GUTTER FLOW CFS	HYDRAULIC EFFICIENCY %
TB45-5	0.50	3.229	0.328	2.792	0.870	4.099	68.11
TB45-5	0.50	3.600	0.342	3.022	1.088	4.688	64.46
TB45-5	0.50	3.989	0.366	3.231	1.425	5.414	59.68
TB45-5	0.50	4.376	0.384	3.418	1.758	6.134	55.72
TB45-5	0.50	4.845	0.401	3.604	2.135	6.980	51.64
TB45-5	0.50	5.319	0.414	3.781	2.494	7.814	48.39
TB45-5	1.00	2.262	0.226	2.072	0.163	2.425	85.44
TB45-5	1.00	3.229	0.261	2.817	0.432	3.661	76.95
TB45-5	1.00	3.600	0.274	3.056	0.570	4.170	73.29
TB45-5	1.00	4.376	0.301	3.484	0.932	5.308	65.64
TB45-5	1.00	4.845	0.324	3.677	1.274	6.119	60.09
TB45-5	1.00	5.319	0.345	3.847	1.647	6.967	55.22
TB45-5	2.80	1.854	0.185	1.709	0.035	1.890	90.44
TB45-5	2.80	2.263	0.214	2.051	0.125	2.389	85.88
TB45-5	2.80	2.680	0.231	2.378	0.219	2.898	82.06
TB45-5	2.80	3.229	0.248	2.751	0.359	3.588	76.67
TB45-5	2.80	3.600	0.264	2.947	0.507	4.107	71.76
TB45-5	2.80	4.363	0.284	3.310	0.785	5.148	64.29
TB45-5	2.80	5.345	0.314	3.724	1.301	6.645	56.05
TB45-5	5.40	1.854	0.212	1.631	0.112	1.966	82.96
TB45-5	5.40	2.676	0.205	2.188	0.111	2.788	78.50
TB45-5	5.40	3.229	0.219	2.531	0.202	3.431	73.78
TB45-5	5.40	3.600	0.232	2.754	0.294	3.894	70.71
TB45-5	5.40	4.376	0.253	3.161	0.523	4.899	64.52
TB45-5	5.40	5.319	0.273	3.503	0.843	6.163	56.85
TB45-5	7.50	1.854	0.178	1.473	0.024	1.878	78.44
TB45-5	7.50	2.262	0.177	1.748	0.026	2.288	76.39
TB45-5	7.50	2.676	0.189	1.990	0.063	2.739	72.67
TB45-5	7.50	3.600	0.210	2.551	0.174	3.774	67.61
TB45-5	7.50	4.376	0.233	2.950	0.372	4.748	62.13
TB45-5	7.50	5.319	0.256	3.266	0.662	5.981	54.60
TB45-5	13.00	0.927	0.116	0.715	0.0	0.927	77.17
TB45-5	13.00	1.854	0.138	1.238	0.0	1.854	66.78
TB45-5	13.00	2.676	0.171	1.738	0.020	2.696	64.46
TB45-5	13.00	3.600	0.183	2.257	0.062	3.662	61.62
TB45-5	13.00	4.376	0.206	2.619	0.188	4.564	57.38
TB45-5	13.00	5.319	0.228	2.970	0.401	5.720	51.92

TEST RESULTS (CONTINUED)

GRATE	SLOPE	RECORDED GUTTER FLOW CFS	WATER DEPTH FT	FLOW INTO GRATE CFS	GUTTER FLOW CORRECTION CFS	TOTAL GUTTER FLOW CFS	HYDRAULIC EFFICIENCY %
TBV-5	0.50	2.676	0.293	2.393	0.524	3.200	74.79
TBV-5	0.50	3.229	0.325	2.758	0.850	4.079	67.61
TBV-5	0.50	3.600	0.338	2.955	1.057	4.657	63.46
TBV-5	0.50	4.376	0.383	3.266	1.742	6.117	53.39
TBV-5	0.50	5.319	0.421	3.516	2.576	7.896	44.53
TBV-5	1.00	0.911	0.148	0.876	0.000	0.911	96.20
TBV-5	1.00	1.854	0.200	1.675	0.065	1.920	87.24
TBV-5	1.00	2.674	0.245	2.230	0.276	2.950	75.60
TBV-5	1.00	3.618	0.275	2.775	0.575	4.193	66.18
TBV-5	1.00	4.363	0.303	3.056	0.951	5.315	57.51
TBV-5	1.00	5.319	0.339	3.328	1.577	6.896	48.26
TBV-5	2.80	0.927	0.141	0.844	0.0	0.927	91.00
TBV-5	2.80	1.854	0.183	1.551	0.032	1.886	82.24
TBV-5	2.80	2.676	0.226	2.082	0.195	2.871	72.50
TBV-5	2.80	3.600	0.259	2.559	0.470	4.070	62.87
TBV-5	2.80	4.376	0.286	2.837	0.803	5.179	54.78
TBV-5	2.80	5.319	0.307	3.060	1.214	6.534	46.84
TBV-5	5.40	0.951	0.134	0.807	0.0	0.951	84.88
TBV-5	5.40	1.854	0.207	1.305	0.092	1.947	67.02
TBV-5	5.40	2.676	0.204	1.850	0.109	2.785	66.42
TBV-5	5.40	3.232	0.227	2.081	0.241	3.474	59.90
TBV-5	5.40	3.600	0.237	2.203	0.332	3.932	56.03
TBV-5	5.40	4.376	0.261	2.382	0.588	4.964	47.99
TBV-5	5.40	5.319	0.274	2.600	0.845	6.165	42.18
TBV-5	7.50	1.351	0.138	0.985	0.0	1.351	72.94
TBV-5	7.50	1.854	0.182	1.162	0.030	1.884	61.69
TBV-5	7.50	2.676	0.189	1.473	0.062	2.738	53.81
TBV-5	7.50	3.600	0.212	1.936	0.188	3.787	51.11
TBV-5	7.50	4.376	0.234	2.199	0.374	4.750	46.29
TBV-5	7.50	5.319	0.252	2.362	0.623	5.943	39.74

TEST RESULTS (CONTINUED)

GRATE	SLOPE	RECORDED GUTTER FLOW CFS	WATER DEPTH FT	FLOW INTO GRATE CFS	GUTTER FLOW CORRECTION CFS	TOTAL GUTTER FLOW CFS	HYDRAULIC EFFICIENCY %
TBV-3	0.50	1.472	0.231	1.470	0.288	1.760	83.51
TBV-3	0.50	1.776	0.256	1.749	0.468	2.244	77.94
TBV-3	0.50	1.980	0.266	1.916	0.581	2.561	74.81
TBV-3	0.50	2.407	0.302	2.243	0.958	3.365	66.65
TBV-3	0.50	2.926	0.331	2.602	1.417	4.343	59.91
TBV-3	1.00	0.501	0.117	0.497	0.000	0.501	99.19
TBV-3	1.00	1.020	0.158	0.983	0.036	1.056	93.14
TBV-3	1.00	1.471	0.193	1.358	0.152	1.623	83.67
TBV-3	1.00	1.990	0.216	1.767	0.317	2.307	76.63
TBV-3	1.00	2.400	0.239	2.033	0.523	2.923	69.54
TBV-3	1.00	2.926	0.267	2.361	0.867	3.793	62.24
TBV-3	2.80	0.510	0.111	0.479	0.0	0.510	93.88
TBV-3	2.80	1.020	0.144	0.910	0.018	1.038	87.70
TBV-3	2.80	1.472	0.178	1.264	0.107	1.579	80.01
TBV-3	2.80	1.980	0.204	1.622	0.259	2.239	72.45
TBV-3	2.80	2.407	0.225	1.877	0.442	2.849	65.90
TBV-3	2.80	2.926	0.242	2.138	0.668	3.594	59.48
TBV-3	5.40	0.523	0.105	0.459	0.0	0.523	87.64
TBV-3	5.40	1.020	0.163	0.767	0.051	1.071	71.63
TBV-3	5.40	1.472	0.160	1.119	0.060	1.532	73.08
TBV-3	5.40	1.778	0.179	1.290	0.133	1.911	67.54
TBV-3	5.40	1.980	0.187	1.389	0.183	2.163	64.24
TBV-3	5.40	2.407	0.205	1.563	0.323	2.730	57.25
TBV-3	5.40	2.926	0.215	1.789	0.465	3.391	52.75
TBV-3	7.50	0.743	0.109	0.567	0.0	0.743	76.34
TBV-3	7.50	1.020	0.143	0.682	0.017	1.037	65.78
TBV-3	7.50	1.472	0.149	0.890	0.034	1.506	59.10
TBV-3	7.50	1.980	0.167	1.214	0.103	2.083	58.29
TBV-3	7.50	2.407	0.184	1.431	0.206	2.613	54.76
TBV-3	7.50	2.926	0.198	1.610	0.343	3.269	49.26

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