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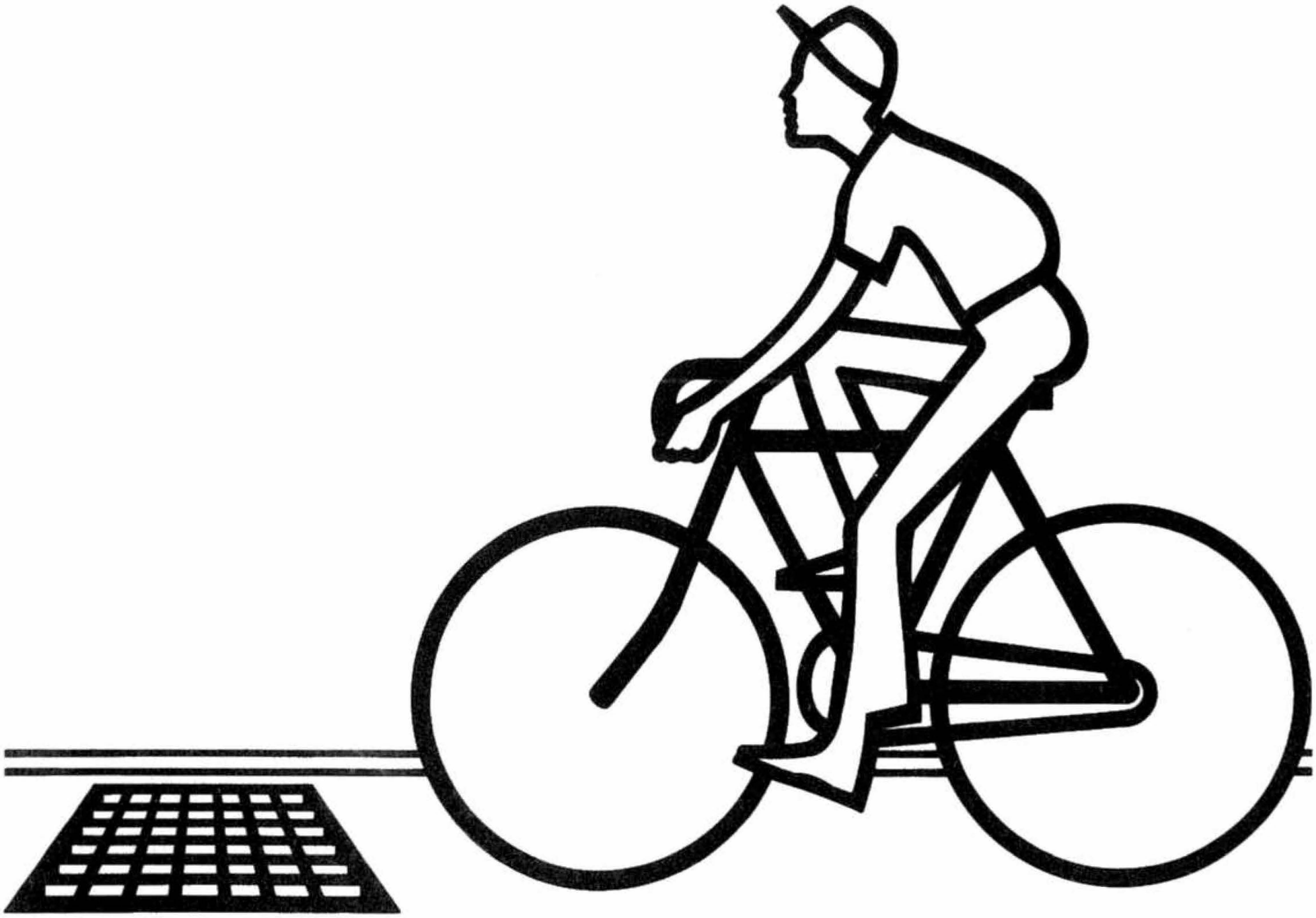
Implementation Package FHWA-IP-80-13

BICYCLE-SAFE GRATE INLETS DESIGN MANUAL



U.S. Department of Transportation
Federal Highway Administration

December 1980

NOTICE

BICYCLE-SAFE GRATE INLETS DESIGN MANUAL

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION

Federal Highway Administration
Offices of Research and Development
Implementation Division

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ABSTRACT

This report presents equations for computing the hydraulic efficiency and discharge for three bicycle-safe grate inlets on a continuous grade and under sump conditions. These three grates were selected based on previous testing of various grates conducted by the Engineering and Research Center of the Water and Power Resources Service in Denver, Colorado. The parallel bar with transverse rods (P-1-7/8-4), the parallel bar with transverse spacers (P-1-1/8), and the curved vane (CV) grates showed the best overall characteristics in safety, hydraulic efficiency, and debris handling. The equations were derived empirically to fit the data within ± 10%. Computer and calculator programs are also included for the user's convenience.

ACKNOWLEDGEMENT

The author wishes to express hearty appreciation to Dr. D.C. Woo and Mr. Robert D. Thomas, Offices of Research and Development, Federal Highway Administration, for their guidance and technical assistance. Without their cooperative effort, this study would not have been completed.

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Fred F.M. Chang

NOTATION

A_g = gross cross-sectional area of grate, W x L
A_o = cross-sectional area of curb opening, h x L
a = exponent for the curvature of side flow
b = experimental coefficient for water surface drawdown, y_d
C_g = discharge coefficient of grate in a sump condition
C_o = discharge coefficient of curb inlet
C_w = weir discharge coefficient
c = experimental coefficient for critical grate length, L_c
E = hydraulic efficiency of grate
ΔE = adjustment for efficiency for unintercepted frontal flow
g = gravitational acceleration
h = height of curb opening
k = experimental coefficient for L_o
L = length of grate
L_c = critical grate length to intercept entire frontal flow
L_o = distance from upstream edge of grate to intersection of side flow and gutter line (see Figure 4)
ΔL = adjustment of weir length to account for flow contraction
m = coefficient related to Manning formula
n = Manning's roughness coefficient
p = coefficient for orifice discharge
Q_i = intercepted gutter flow
Q_T = total gutter discharge
Q_w = discharge through grate under weir flow condition
Q_o = discharge through grate under orifice flow condition
q = exponent for orifice discharge coefficient
R_f = ratio of unintercepted frontal flow to total gutter flow
R_s = ratio of unintercepted side flow to total gutter flow
S_o = longitudinal roadway slope
T = width of spread
W = width of grate
y = flow depth
y_d = depth of water surface drawdown
Z = reciprocal of roadway cross slope

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INTRODUCTION

The Engineering and Research Center of the Water and Power Resources Service (formerly the Bureau of Reclamation) in Denver, Colorado, has completed testing of 11 inlet grates for the Federal Highway Administration. Seven of these grates were found to be bicycle-safe. These seven grates were then tested thoroughly for their hydraulic efficiency and debris handling capability on continuous grades.

Two grate sizes were tested: 2 ft by 2 ft (0.61 m by 0.61 m) and 2 ft by 4 ft (0.61 m by 1.22 m). From the test results, three grates were selected as possessing the best overall characteristics. These findings are presented in FHWA-RD-77-24 (1)*. These three grates were further tested for various sizes, and the findings are presented in FHWA-RD-78-4 (2). The three grates were then tested in a sump condition, and the results are presented in FHWA-RD-78-70 (3).

The three grates selected as possessing the best overall characteristics are the parallel bar with transverse rods (P-1-7/8-4), the parallel bar with transverse spacers (P-1-1/8), and the curved vane (CV). The dimensions of these three grates are shown in Figures 1, 2, and 3, respectively. Performance testing of these three grates covered the following ranges:

Grate size: 1.25 ft to 3 ft (0.38 m to 0.91 m) in width and 2 ft to 4 ft (0.61 m to 1.22 m) in length
Road surface roughness: Manning's $n = 0.016$
Road cross slope: 1:96 to 1:16
Road longitudinal slope 0 to 0.13
Maximum gutter flow: 5.5 cfs (0.156 m^3/s) for grates on a continuous grade and 30 cfs (0.85 m^3/s) for sump grates

Based on the data from this testing, an analysis was made to develop empirical equations relating flow characteristics, road geometry and the type and size of grate.

This manual presents the resulting equations for determining the hydraulic efficiencies of the three grates on a continuous grade and the discharge-depth relationship in a sump condition. The detailed analyses of the hydraulic characteristics, the derivation of the equations, and a comparison of the results with experimental data are included in the Appendix.

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*Number in parentheses refers to References on page 34.

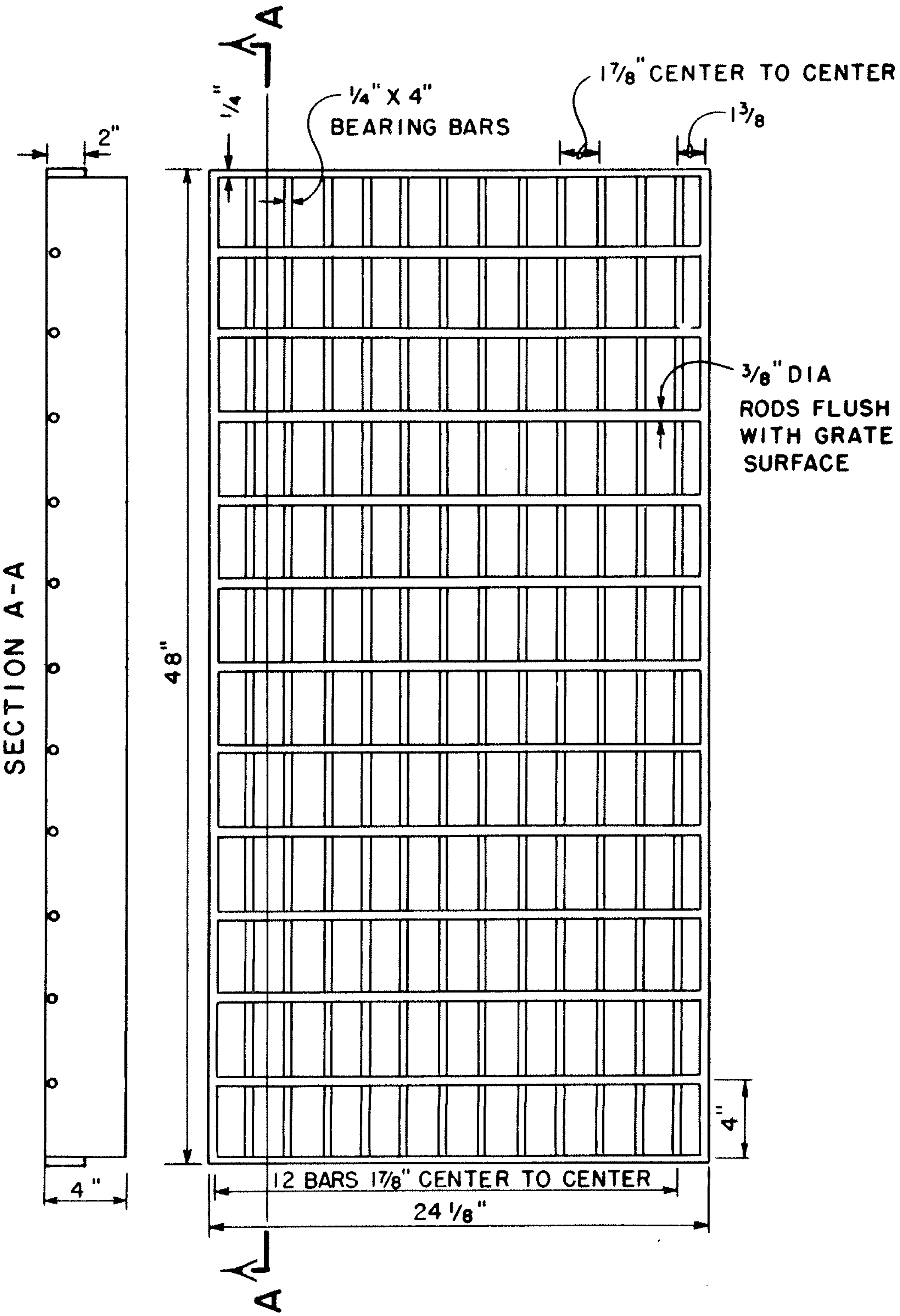


Figure 1. 2 ft by 4 ft (0.61 m by 1.22 m) fabricated steel P - 1-7/8 - 4 grate.

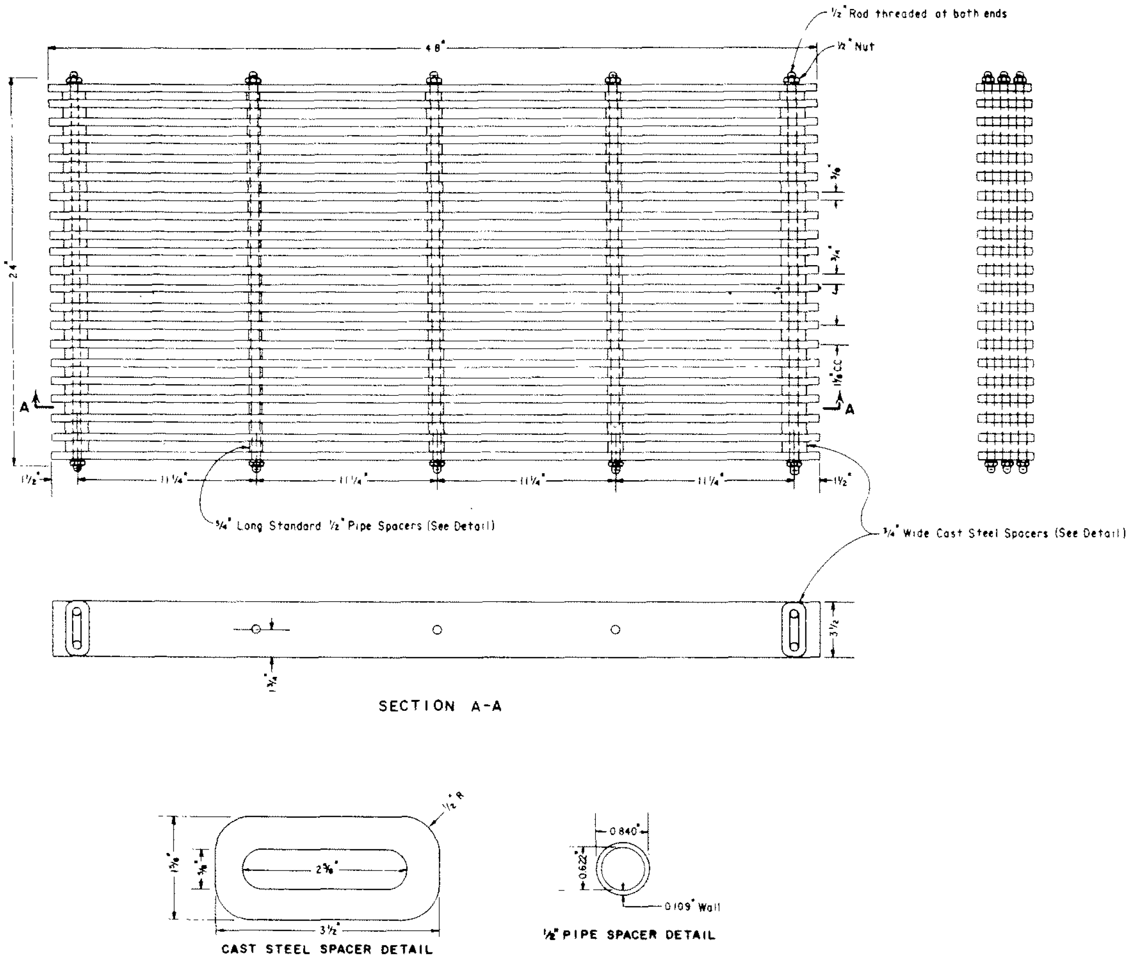


Figure 2 2 ft by 4 ft (0.61 m by 1.22 m) fabricated steel P - 1-1/8 grate (Note: 1 in = 25.4 mm).

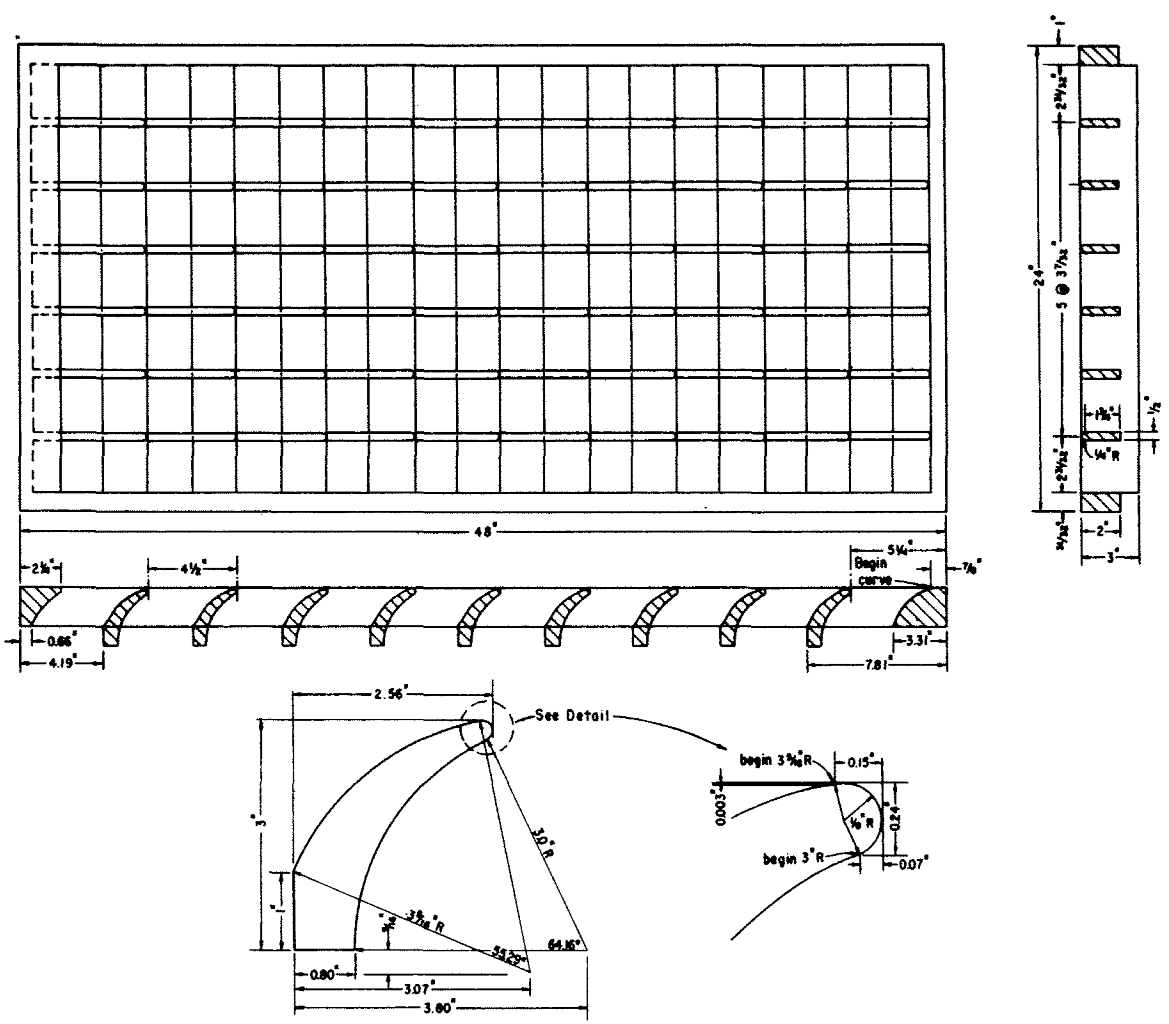


Figure 3 2 ft by 4 ft (0.61 m by 1.22 m) curved vane grate (Note: 1 in = 25.4 mm).

DESIGN CONSIDERATIONS

In grate inlet design, the determination of type, size, and spacing of the grate to intercept a specified portion of the design gutter discharge is of general concern. In addition, for optimum design of the entire drainage system and for the analysis of flow conditions in the system, the discharge capacity curve for each grate must be developed. Using this curve and the hydrograph of the design gutter flow, the inlet hydrograph of the grate can be derived to simulate flow in the drainage system. In this report, an emphasis was placed on the development of hydraulic performance curves for the three grates.

Selection of Grate Type

Grate type selection should consider such factors as safety, structural strength, debris handling characteristics, hydraulic efficiency, and cost. Among various grates tested, Burgi and Gober (1) recommended the parallel bar with transverse rods (P-1-7/8-4), the parallel bar with transverse spacers (P-1-1/8), and the curved vane (CV) for their superior overall performance. The dimensions of these grates are shown in Figures 1, 2, and 3.

For grates on a continuous grade, the curved vane grates performed better in debris handling but not as well in bicycle safety than the other two grates. For grates in a sump condition, the P-1-1/8 grate performed slightly better in debris handling. For the three grates on a continuous grade, no significant differences in hydraulic efficiencies were recognized at lower discharges. The CV and the P-1-7/8-4 grates, however, performed slightly better at higher discharges. For grate inlets in a sump condition, the performance of the grates under weir control was identical for larger grates with low discharges. For smaller grates with higher discharge and orifice flow, the P-1-7/8-4 grates performed slightly better.

Since no single grate type outranked the others in all aspects, judgment must be exercised in selecting a grate. Bicycle safety and debris handling capabilities must be weighed carefully in the final grate selection.

Grate Size and Spacing

For economical reasons, grate sizes are usually standardized by the State for use on its highways. The selection of those standard sizes is normally dictated by such factors as cost (construction and maintenance cost of the grate, the catch basin, and the connection to the main sewer), safety for passing traffic, structural strength, hydraulic efficiency, and debris accumulation. The determination of size and spacing of a grate in the field is based on the criteria of allowable maximum gutter flow width and the grate's efficiency characteristics. In a sump condition, the allowable maximum water depth at the low point of a sag vertical curve is the dominant factor in selecting the size and spacing of a grate.

It is common practice to specify the grate one size larger than actually needed as a precautionary measure against complete plugging by debris. The analytical method presented here can be used in the preliminary investigation for the selection of the standardized size.

Summary of Equations for Hydraulic Efficiency and Discharge of Grate Inlets

A. Grate Inlets on a Continuous Grade:

Flow at a grate inlet on a continuous grade is often divided into two parts: (1) frontal flow that directly passes over the upstream edge of the grate, and (2) the remaining part generally called side flow. The amount of interception of the flow depends on discharge, road geometry, and the type and size of the grate.

A sketch of a typical flow pattern at a grate inlet on a continuous grade is shown in Figure 4. This flow pattern actually represents that of higher flow when both the frontal flow and side flow are partially intercepted. For lower flow, however, the flow pattern is different: the frontal flow and side flow may be totally intercepted. With decreases in the gutter discharge, the side flow diminishes and the gutter flow consists of only the frontal flow.

Because of these differences in the flow pattern, a set of equations was developed to determine the hydraulic efficiency of an inlet grate for all ranges of gutter discharges. These equations are summarized in Table 1. Equation (1) is a different form of the integrated Manning's equation (with $n = 0.016$) derived by Izzard (4). Flow depths y_1 at the curb and y_2 at a distance W (grate width) from the curb can be computed from Eqs. (1) and (2). The distance L_0 where the water surface intersects with the gutter line can be obtained from Eq. (3). Length L_c in Eq. (4) is the critical length of the grate over which total frontal flow interception occurs. Equation (5) gives hydraulic efficiency when the entire frontal flow is intercepted ($L_c < L$). The second term on the right side of this equation is the ratio of unintercepted side flow to the total gutter flow. If y_2 is negative or L_0 is less than L, indicating no side flow or total interception of the side flow, this term must equal zero and the hydraulic efficiency becomes 100 percent. In case of partial frontal flow interception ($L_c > L$), the hydraulic efficiency determined above must be reduced by the amount ΔE. The value of ΔE is the ratio of the unintercepted frontal flow to the total gutter flow and can be determined from either Eq. (6) or Eq. (7), whichever is appropriate.

In summary, to determine the hydraulic efficiency of a grate, the flow pattern must be identified first, and the correct equations must be selected. For the user's convenience, a nomograph for Eq. (5) is shown in Figure 5, and Eqs. (6) and (7) are jointly plotted in Figure 6.

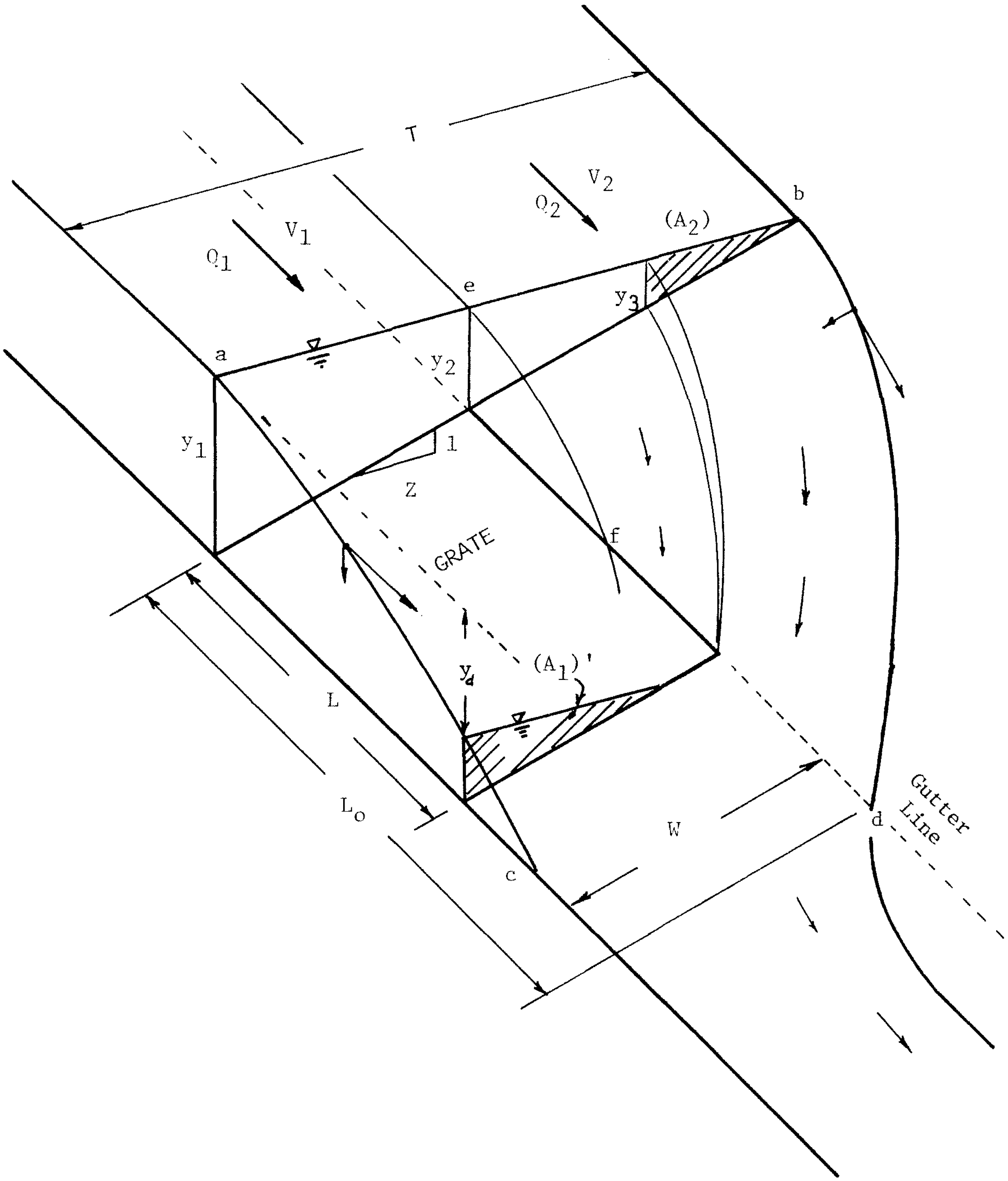


FIGURE 4 FLOW AT A GRATE INLET ON A CONTINUOUS GRADE

TABLE 1 Equations for Grate Inlets on a Continuous Grade

$$y_1 = \left(\frac{Q_T}{m\, S_o^{0.5}\, Z}\right)^{0.375} \quad \text{or} \quad Q_T = m\, S_o^{0.5}\, Z\, y_1^{2.67} \qquad (1)$$

$$y_2 = y_1 - W/Z \qquad (2)$$

$$L_o = k\, S_o^{0.65}\, y_2^{1.17}\, Z \qquad (3)$$

$$L_c = c\left(\frac{Q_T\, S_o}{Z}\right)^{0.67} \qquad (4)$$

Grate Efficiency:

for $(L/L_c) \geq 1$,

$$E = Q_i/Q_T = 1 - (y_2/y_1)^{2.67}\{1 - (L/L_o)^a\}^{2.67} \qquad (5)$$

Adjustment for Efficiency (subtract from E):

for $(y_2/y_1) \leq (L/L_c)^{0.56} < 1$,

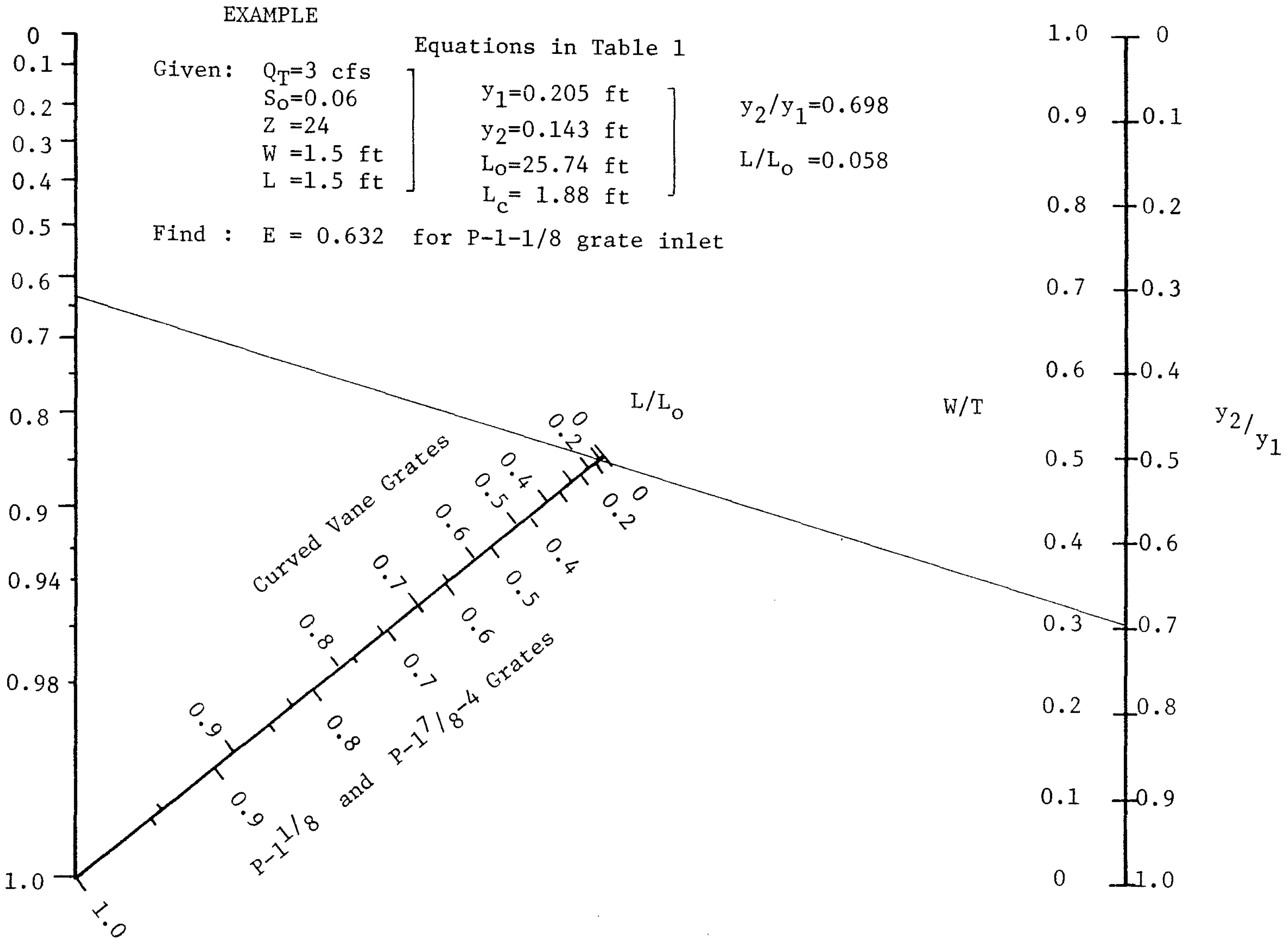
$$\Delta E = \{1 - (y_2/y_1)^{2.67}\}\left(\frac{\{1 - (L/L_c)^{0.56}\}^2}{1 - (y_2/y_1)^2}\right) \qquad (6)$$

for $(L/L_c)^{0.56} < (y_2/y_1) < 1$,

$$\Delta E = \{1 - (y_2/y_1)^{2.67}\}\left(1 - \frac{2(L/L_c)^{0.56}}{1 + (y_2/y_1)}\right) \qquad (7)$$

Values of Experimental Coefficients:

	a	c		m		k	
		English	SI	English	SI	English	SI
P-1-7/8-4	1.5	85	290	34.8	23.4	65	79
P-1-1/8	↓	50	165	↓	↓	↓	↓
Curved Vane	1.8	↓	↓				



EXAMPLE

Equations in Table 1

Given: Q_T=3 cfs
S_o=0.06
Z =24
W =1.5 ft
L =1.5 ft

y_1=0.205 ft
y_2=0.143 ft
L_o=25.74 ft
L_c= 1.88 ft

y_2/y_1=0.698
L/L_o =0.058

Find : E = 0.632 for P-1-1/8 grate inlet

FIGURE 5 Nomograph for Grate Efficiency for 100 percent Frontal Flow Interception

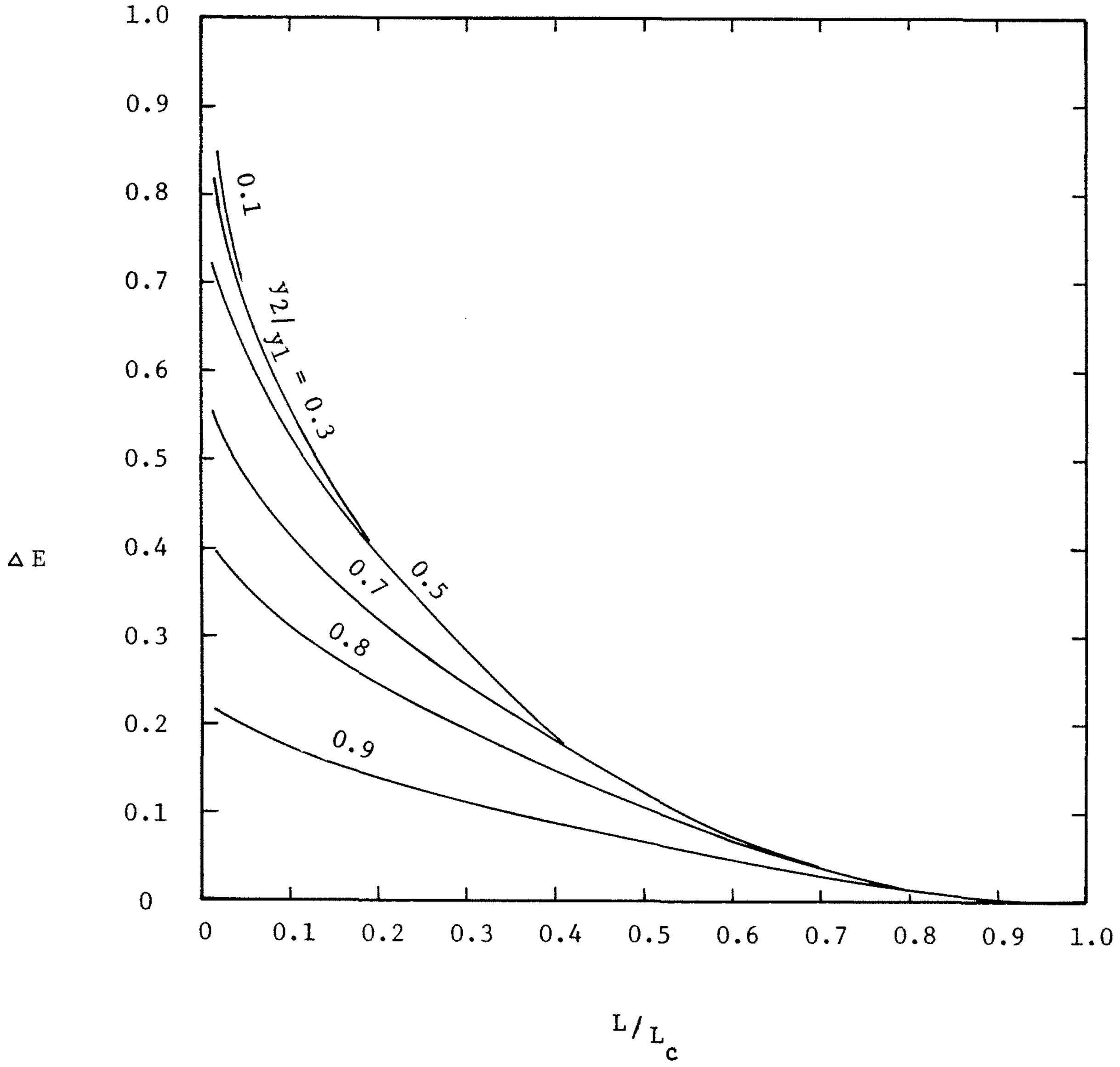


FIGURE 6 Ratio of Unintercepted Frontal Flow to Total Flow

B. Grate Inlets in a Sump Condition:

Flow at a grate inlet in a sump condition assumes weir flow, orifice flow, or transitional flow conditions depending on flow depth. Weir flow condition prevails at shallow depth and orifice flow at a depth which submerges the grate. Transitional conditions exist between these flows. In this study, the transition zone was found to be at a depth of about $0.43\ L^{0.7}$ for all three grates.

The general equations for weir flow and orifice flow were modified to account for the roadway cross slope and a curb opening provided along the entire length of the sump grate. These modified weir and orifice equations are presented in Table 2. The discharges in Eqs. (8) and (9) are total discharges assuming the flow converges equally from both sides of the grate at a dip in the road. The first term on the right side of Eq. (9) is the discharge through the curb opening. If no curb opening is present for a sump grate, this term must be eliminated.

For very shallow flow when the flow spread is narrower than the grate width ($T < W$, or $y_2 < 0$), y_2 in Eq. (8) equals zero. In the transitional zone, either Eq. (8) or Eq. (9) may be used; this leads to only a minor discrepancy as demonstrated later in Figure 9. A better result can be obtained by taking the average of both values.

TABLE 2 Equations for Grate Inlets in a Sump Condition

I. Weir Flow Condition: $y_1 \le 0.43\ L^{0.7}$(English); $y_1 \le 0.3\ L^{0.7}$(SI)

$$Q_W = C_W\left[(L - y_2)y_2^{1.5} + 0.707W(y_1 + y_2)^{1.5}\right] \qquad (8)$$

$C_w = 3.5$ (English), 1.93 (SI)

II. Orifice Flow Condition:

$$Q_O = 0.7\ A_O\left[2g(y_1 - h/2)\right]^{0.5} + C_g A_g\left[g(y_1 + y_2)\right]^{0.5} \qquad (9)$$

$$C_g = p(y_1 + y_2)^q / L^{0.5}$$

	p		q
	English	SI	
P-1-7/8-4	0.34	0.49	0.8
P-1-1/8	0.30	0.38	0.7
Curved Vane	o.32	0.24	0.25

Note: If no curb opening is present, delete the first term from Eq. (9)

EXAMPLE PROBLEMS

Applications of the equations in Tables 1 and 2 to develop hydraulic performance curves for grate inlets are presented below. Two example problems are included: one is for grate inlets on a continuous grade and the other for grates in a sump condition. In both cases an 18 in. by 18 in. P-1-1/8 grate is used as a State standard.

A. Grate Inlets on a Continuous Grade

Three different sizes are used to demonstrate the effect of grate width and length on hydraulic efficiency: 18 in. X 18 in. (W X L), 36 in. X 18 in. (two grates aligned side by side), and 18 in. X 36 in. (two grates aligned end to end). Step-by-step example computations are shown below, and the hydraulic performance curves for a gutter discharge of up to 5 cfs are presented in Figures 7 and 8 for longitudinal roadway slopes of 1 and 6 percent, respectively.

Example Computation:

Given: $Q_T = 3.0$ cfs; $S_o = 6\%$; $Z = 24$; $W = 18$ in.; $L = 18$ in.; Grate: P-1-1/8

Required: Compute hydraulic efficiency

Solution:

1. Compute flow depths y_1 and y_2 :

$$y_1 = \left(\frac{Q_T}{34.8\ S_o^{0.5}\ Z}\right)^{0.375} = \left(\frac{3.0}{34.8(0.06)^{0.5}(24)}\right)^{0.375} = 0.205 \text{ ft}$$

$$y_2 = y_1 - W/Z = 0.205 - 1.5/24 = 0.143 \text{ ft}$$

2. Compute lengths L_o and L_c :

$$L_o = kS_o^{0.65}\ y_2^{1.17}\ Z = 65(0.06)^{0.65}(0.143)^{1.17}(24) = 25.74 \text{ ft}$$

$$L_c = c\ \left(\frac{Q_T\ S_o}{Z}\right)^{0.67} = 50\ \left(\frac{3 \times 0.06}{24}\right)^{0.67} = 1.88 \text{ ft}$$

3. Compute efficiency E :

$$E = 1 - (y_2/y_1)^{2.67} \left(1 - (L/L_0)^a \right)^{2.67}$$

$$= 1 - (0.143/0.205)^{2.67} \left(1 - (1.5/25.74)^{1.5} \right)^{2.67} = 0.632$$

Alternately, the nomograph in Figure 5 can be used:

For $y_2/y_1 = 0.143/0.205 = 0.698$ and $L/L_0 = 1.5/25.74 = 0.0582$,

$E = 0.632$

4. Compute efficiency adjustment ΔE, if needed.

Since $L/L_c = 1.5/1.88 = 0.798 < 1$, an adjustment is needed. Equation (6) should be used for the adjustment since $y_2/y_1 = 0.698$ is less than $(L/L_c)^{0.56} = (1.5/1.88)^{0.56} = 0.881$.

$$\Delta E = \left(1 - (y_2/y_1)^{2.67} \right) \left(\frac{\left(1 - (L/L_c)^{0.56}\right)^2}{1 - (y_2/y_1)^2} \right)$$

$$= \left(1 - (0.698)^{2.67} \right) \left(\frac{(1 - 0.881)^2}{1 - (0.698)^2} \right) = 0.017$$

Alternately, from the chart in Figure 6, for $y_2/y_1 = 0.698$ and $L/L_c = 0.798$,

$\Delta E = 0.017$

5. The hydraulic efficiency of the grate is

$E - \Delta E = 0.632 - 0.017 = 0.615$

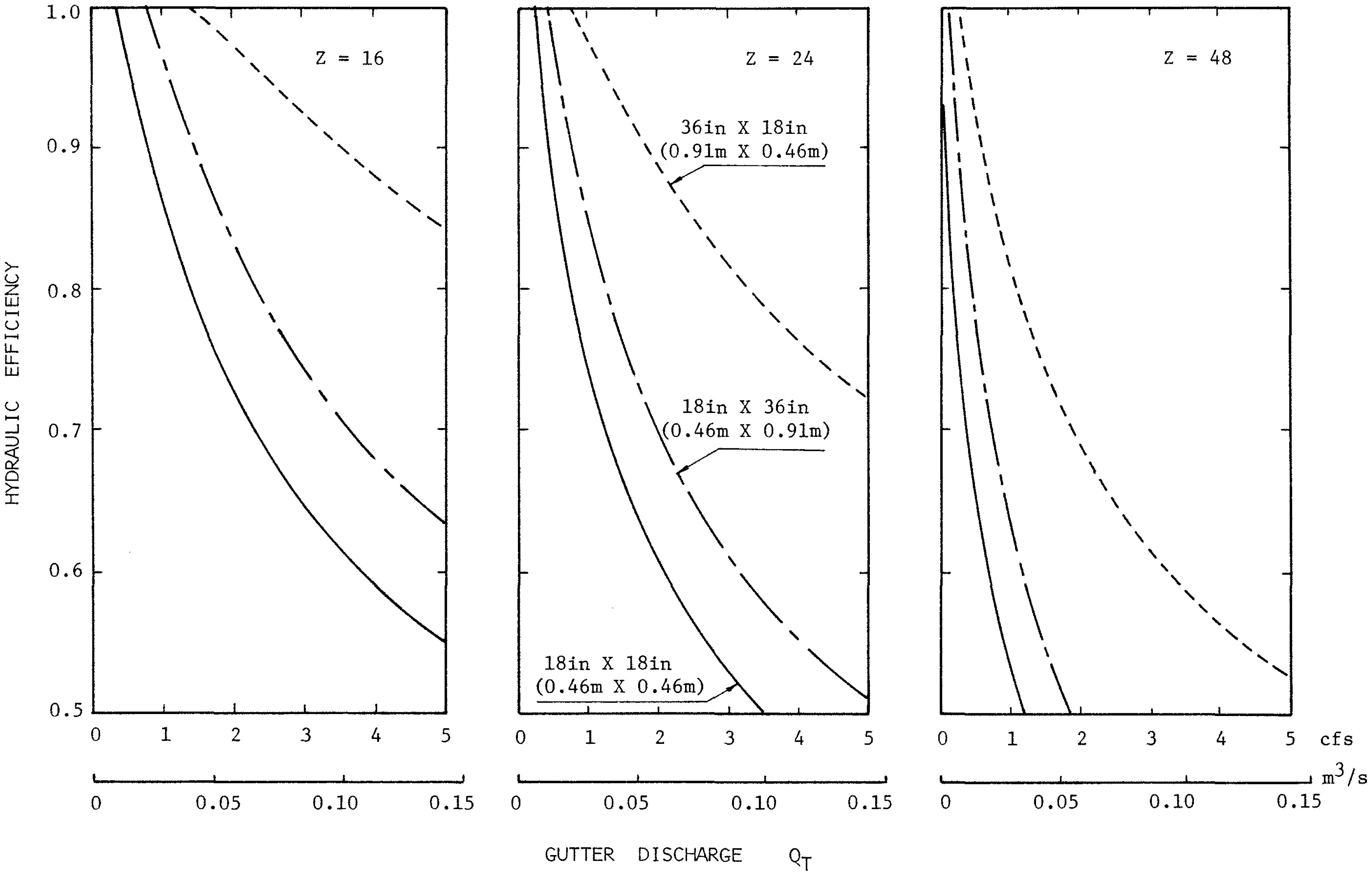


FIGURE 7 HYDRAULIC EFFICIENCY VS. GUTTER FLOW FOR THE P-1-1/8 GRATE, $S_0 = 0.01$

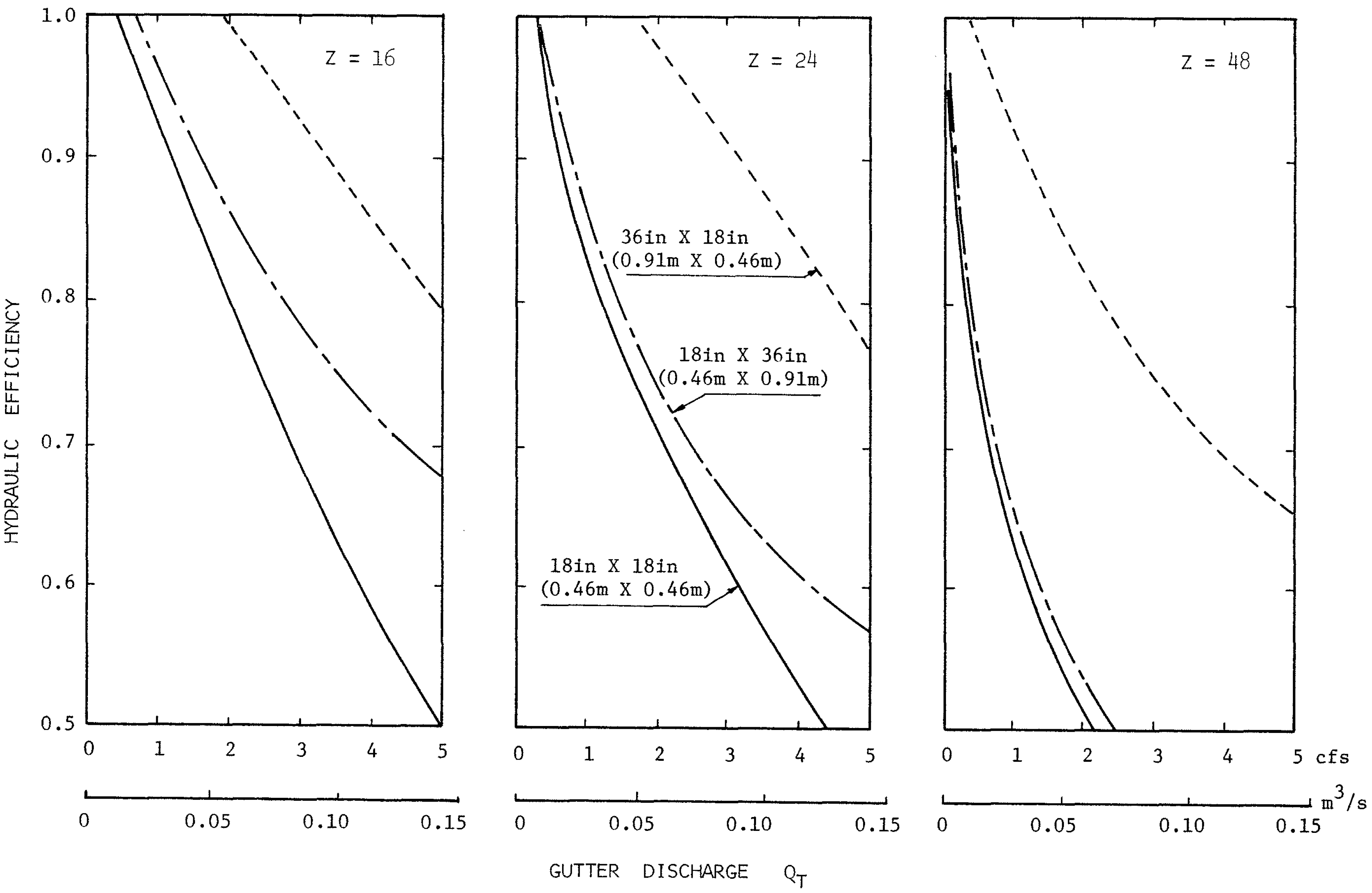


FIGURE 8 HYDRAULIC EFFICIENCY VS. GUTTER FLOW FOR THE P-1-1/8 GRATE, $S_0 = 0.06$

B. Grate Inlets in a Sump Condition

Grate inlets in a sump condition are required to intercept all gutter flow at a sump depth not exceeding the maximum allowable depth. Therefore, for a sump grate, the major concern is to develop the depth-discharge relationship. Two different grate sizes are used to show the effect of size: 18 in. X 18 in. (W X L) and 18 in. X 36 in. (two grates aligned end to end). Example computations are presented below, and the depth-discharge relationships for the two grates up to discharges of 18 cfs are shown in Figure 9. In all cases, the sump grate has a curb opening of 4 in. height and with a length equal to the length of the grate.

Example Computation:

Given: $y_1 = 0.5$ ft; $Z = 24$; $W = 18$ in.; $L = 18$ in.;
Grate: P-1-1/8

Required: Determine discharge

Solution:

1. Determine the type of flow (weir or orifice):

   Since $y_1 = 0.5 \text{ ft} < 0.43\, L^{0.7} = 0.43\,(18/12)^{0.7} = 0.571 \text{ ft}$,

   the flow is under weir flow condition, and Eq. (8) must be used to determine the discharge.

2. Compute the discharge:

   $$y_2 = y_1 - W/Z = 0.5 - 1.5/24 = 0.438 \text{ ft}$$

   $$\begin{aligned} Q_w &= 3.5\left[(L - y_2)y_2^{1.5} + 0.707W(y_1 + y_2)^{1.5}\right] \\ &= 3.5\left[(1.5 - 0.438)(0.438)^{1.5} + 0.707(1.5)(0.5 + 0.438)^{1.5}\right] \\ &= 4.45 \text{ cfs} \end{aligned}$$

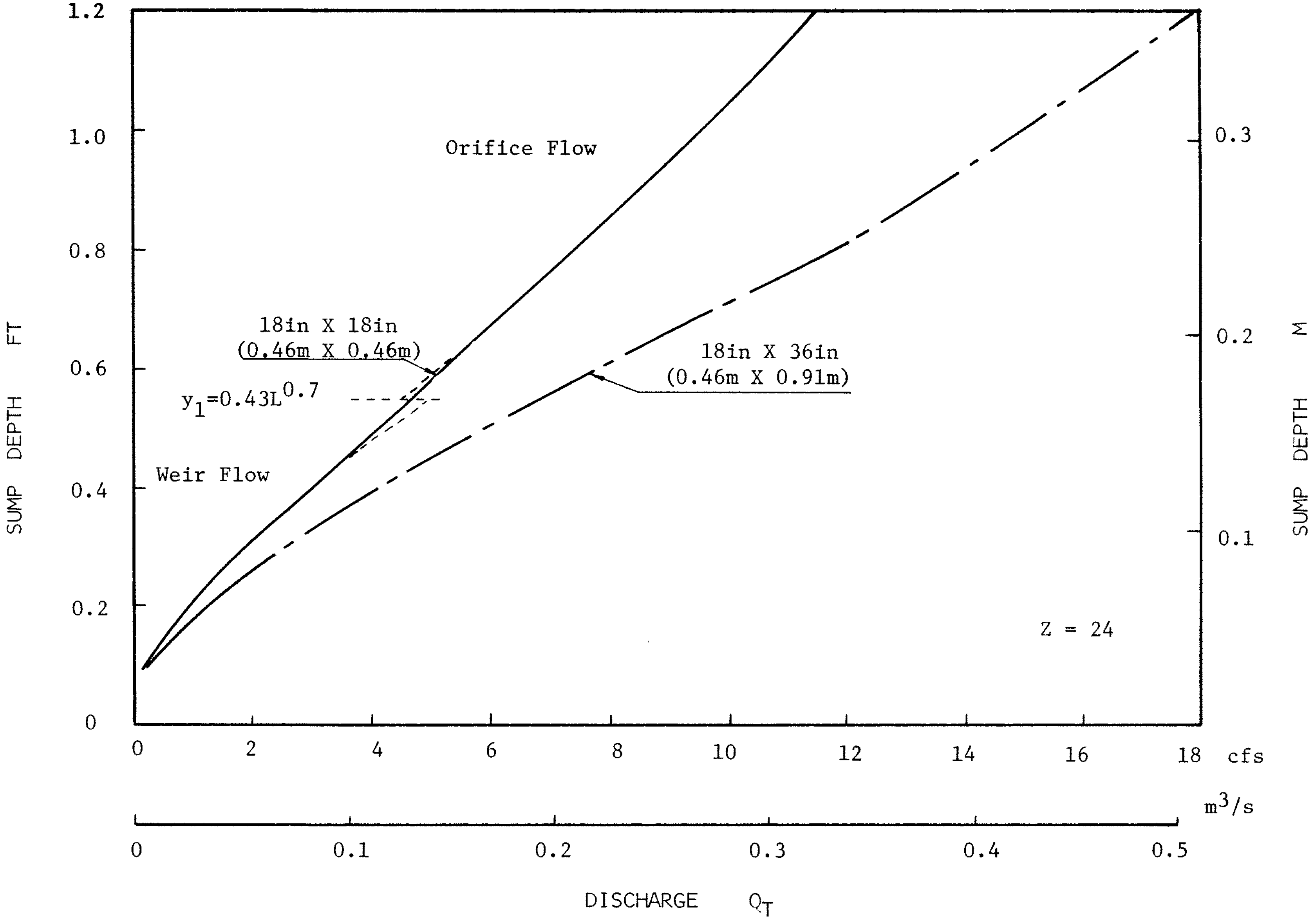


FIGURE 9 INLET CAPACITY CURVE, P-1-1/8 SUMP GRATES, Z = 24

COMPUTER AND CALCULATOR PROGRAMS

Computer and calculator programs for computing hydraulic efficiencies for three bicycle-safe grates on a continuous grade and for computing discharges in a sump condition were developed. The computer programs are written in FORTRAN IV and the calculator programs are developed for the TI58/TI59 and for the HP67/97 calculators. All equations are listed in Tables 1 and 2.

A. Hydraulic Efficiencies of Grates on a Continuous Grade

Input and output parameters for all programs for computing hydraulic efficiencies for the three grates on a continuous grade are as follows:

Input Data:

Q_T - gutter discharge
S_o - longitudinal roadway slope
Z - reciprocal of roadway cross slope
W - width of grate
L - length of grate
m - coefficient related to Manning's equation
k - experimental coefficient for L_o
a - exponent for the curvature of side flow
c - experimental coefficient for critical grate length

Output:

Q_T - gutter discharge
E - hydraulic efficiency of grate

The following examples may be used to test the programs for hydraulic efficiency of grate inlets on a continuous grade:

Q_T	S_o	Z	W	L	m	k	a	c	E
0.5	0.03	16	1.5	3.0	34.8	65	1.5	85	1.000
1.5	0.03	16	1.5	3.0	↓	↓	1.5	85	0.889
2.0	0.04	24	1.5	2.0			1.8	50	0.673
3.0	0.06	24	1.5	1.5			1.5	50	0.617
4.5	0.09	48	2.0	4.0			1.5	50	0.548

```
C       THIS PROGRAM COMPUTES GRATE HYDRAULIC EFFICIENCY
        READ(5,1)QT,S,Z,W,AL,CM,CK,CA,CC
1       FORMAT(F5.2,F6.5,F3.1,2F5.2,F4.1,F3.0,F3.1,F3.0)
        IF(QT)190,190,191
190     E=1.0
        GO TO 290
191     Y1=(QT/(CM*S**0.5*Z))**0.375
        Y2=Y1-W/Z
        ALC=CC*(QT*S/Z)**0.67
        RL=(AL/ALC)**0.56
C       CHECK EXISTANCE OF SIDE FLOW. IF NO SIDE FLOWY2=0
        IF(Y2.LT.0.)Y2=0.
        Y=Y2/Y1
        ALZ=CK*S**0.65*Y2**1.17*Z
C       CHECK IF 100% SIDE FLOW INTERCEPTION
        IF(ALZ/AL.GT.1.0)GO TO 200
        E=1.0
        GO TO 205
C       HYDRAULIC EFFICIENCY OF GRATE
200     E=1.-(Y*(1.-(AL/ALZ)**CA))**2.67
C       CHECK IF ADJUSTMENT FOR EFFICIENCY IS NEEDED
205     IF(RL.GE.1.0)GO TO 290
        IF(Y-RL)210,290,220
C       ADJUSTMENT WHEN DRAWDOWN IS GREATER THAN Y2
210     DELE=(1.-Y**2.67)*(1.-RL)**2./(1.-Y**2.)
        GO TO 250
C       ADJUSTMENT WHEN DRAWDOWN IS LESS THAN Y2
220     DELE=(1.-Y**2.67)*(1.-2.*RL/(1.+Y))
250     E=E-DELE
290     WRITE(6,2)QT,E
2       FORMAT(1X,13H DISCHARGE = ,F5.2,17H   EFFICIENCY E= ,F6.4)

        STOP
        END
```

TITLE Efficiency of Grate Inlets PAGE 1 OF 3

PROGRAMMER ______ DATE ______

TI Programmable
Program Record

Partitioning (Op 17) ⌊ ⌋ Library Module ______ Printer ______ Cards ______

TI 58/59

PROGRAM DESCRIPTION

This program is designed to compute the hydraulic efficiency of the three bicycle-safe grate inlets(P-1-1/8, P-1-7/8-4, Curved Vane) on a continuous grade. The equations used in the program are listed in Table 1.

Note: For TI-58, the memory area must be repartitioned to accomodate the program and all printing instructions should be ignored.

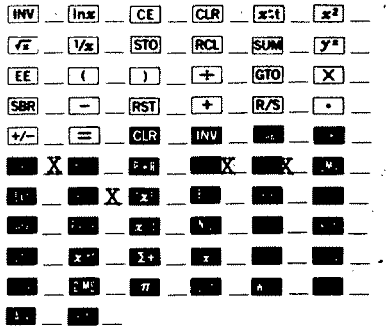
USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Input					
	Total gutter discharge	Q_T	A			Q_T
	Longitudinal roadway slope	S_o	B			S_o
	Reciprocal of road cross slope	Z	C			Z
	Width of grate	W	D			W
	Length of grate	L	E			L
2	Input coefficients					
		m	2nd	A		m
		k	2nd	B		k
		a	2nd	C		a
		c	2nd	D		c
3	Compute hydraulic efficiency		2nd	E		E

USER DEFINED KEYS		
A	Gutter discharge	
B	Road slope	S_o
C	Cross slope	Z
D	Grate width	W
E	Grate length	L
A'	Coefficient	m
B'	Coefficient	k
C'	Coefficient	a
D'	Coefficient	c
E'		

DATA REGISTERS (INV ■)			
0		10	E
1	Q_T	1	y_1
2	S_o	2	y_2
3	Z	3	y_2/y_1
4	W	4	L/L_c
5	L	5	$(L/L_c)^{0.56}$
6	m	6	
7	k	7	
8	a	8	
9	c	9	

LABELS (Op 08)



FLAGS 0	1	2	3	4	5	6	7	8	9

TITLE Efficiency of Grate Inlets PAGE 2 OF 3

PROGRAMMER ______ DATE ______

TI Programmable
Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
0	76	Lbl		55	07	7	TI 59	110	05	05	
	11	A			69	Op	only		55	÷	
	42	STO			04	04	"		53	(	
	01	01			01	1			43	RCL	
	22	INV			42	STO			07	07	
	77	GE		60	10	10			65	x	
	49	Prd			43	RCL			43	RCL	
	67	EQ			06	06			02	02	
	49	Prd			65	x			45	y^x	
	91	R/S			43	RCL			93	.	
10	76	Lbl			03	03		120	06	6	
	12	B			65	x			05	5	
	42	STO			43	RCL			65	x	
	02	02			02	02			43	RCL	
	91	R/S			34	$\sqrt{x}$			12	12	
	76	Lbl		70	95	=			45	y^x	
	13	C			35	1/x			01	1	
	42	STO			65	x			93	.	
	03	03			43	RCL			01	1	
	91	R/S			01	01			07	7	
20	76	Lbl			95	=		130	65	x	
	14	D			45	y^x			43	RCL	
	42	STO			93	.			03	03	
	04	04			03	3			54	)	
	91	R/S			07	7			54	)	
	76	Lbl		80	05	5			45	y^x	
	15	E			95	=			43	RCL	
	42	STO			42	STO			08	08	
	05	05			11	11			54	)	
	91	R/S			75	-			95	=	
30	76	Lbl			43	RCL		140	22	INV	
	16	A'			04	04			77	GE	
	42	STO			55	÷			38	Sin	
	06	06			43	RCL			45	y^x	
	91	R/S			03	03			02	2	
	76	Lbl		90	95	=			93	.	
	17	B'			42	STO			06	6	
	42	STO			12	12			07	7	
	07	07			55	÷			95	=	
	91	R/S			43	RCL			94	+/-	
40	76	Lbl			11	11		150	85	+	
	18	C'			95	=			01	1	
	42	STO			42	STO			95	=	
	08	08			13	13			42	STO	
	91	R/S			22	INV			10	10	
	76	Lbl		100	77	GE			43	RCL	
	19	D'			38	Sin			09	09	
	42	STO			43	RCL			65	x	
	09	09			13	13			53	(	
	91	R/S			65	x			43	RCL	
50	76	Lbl			53	(					
	10	E'			01	1					
	06	6	TI 59		75	-					
	04	4	only		53	(					
	01	1	"		43	RCL					

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

TITLE Efficiency of Grate Inlets PAGE 3 OF 3

PROGRAMMER ______ DATE ______

TI Programmable
Coding Form

LOC	CODE	KEY	COMMENTS
160	01	01	
1	65	x	
2	43	RCL	
3	02	02	
4	55	÷	
5	43	RCL	
6	03	03	
7	54	)	
8	45	y^x	
9	93	.	
170	06	6	
1	07	7	
2	95	=	
3	35	1/x	
4	65	x	
5	43	RCL	
6	05	05	
7	95	=	
8	42	STO	
9	14	14	
180	75	−	
1	01	1	
2	95	=	
3	77	GE	
4	38	Sin	
5	43	RCL	
6	14	14	
7	45	y^x	
8	93	.	
9	05	5	
190	06	6	
1	95	=	
2	42	STO	
3	15	15	
4	75	−	
5	43	RCL	
6	13	13	
7	95	=	
8	22	INV	
9	77	GE	
200	30	Tan	
1	53	(	
2	01	1	
3	75	−	
4	43	RCL	
5	13	13	
6	45	y^x	
7	02	2	
8	93	.	
9	06	6	
210	07	7	
1	54	)	
2	65	x	
3	53	(	
4	01	1	

LOC	CODE	KEY	COMMENTS
215	75	−	
6	43	RCL	
7	15	15	
8	54	)	
9	33	x^2	
220	55	÷	
1	53	(	
2	01	1	
3	75	−	
4	43	RCL	
5	13	13	
6	33	x^2	
7	54	)	
8	95	=	
9	94	+/−	
230	85	+	
1	43	RCL	
2	10	10	
3	95	=	
4	69	Op	TI 59
5	06	06	only
6	91	R/S	
7	76	Lbl	
8	30	Tan	
9	53	(	
240	01	1	
1	75	−	
2	43	RCL	
3	13	13	
4	45	y^x	
5	02	2	
6	93	.	
7	06	6	
8	07	7	
9	54	)	
250	65	x	
1	53	(	
2	01	1	
3	75	−	
4	02	2	
5	65	x	
6	43	RCL	
7	15	15	
8	55	÷	
9	53	(	
260	01	1	
1	85	+	
2	43	RCL	
3	13	13	
4	54	)	
5	54	)	
6	95	=	
7	94	+/−	
8	85	+	
9	43	RCL	

LOC	CODE	KEY	COMMENTS
270	10	10	
1	95	=	
2	69	Op	TI 59
3	06	06	only
4	91	R/S	
5	76	Lbl	
6	38	Sin	
7	43	RCL	
8	10	10	
9	69	Op	TI 59
280	06	06	only
1	91	R/S	
2	76	Lbl	
3	49	Prd	
4	69	Op	TI 59
5	00	00	only
6	03	3	
7	01	1	
8	03	3	
9	02	2	
290	00	0	
1	00	0	
2	04	4	
3	03	3	
4	69	Op	
5	01	01	
6	01	1	
7	03	3	
8	03	3	
9	07	7	
300	01	1	
1	07	7	
2	03	3	
3	05	5	
4	00	0	
5	00	0	
6	69	Op	
7	02	02	
8	07	7	
9	01	1	
310	00	0	
1	00	0	
2	00	0	
3	00	0	
4	00	0	
5	00	0	
6	69	Op	
7	03	03	
8	69	Op	
9	05	05	
320	25	CLR	
	91	R/S	

64 [illegible] Ind 74 SUM Ind 92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

USER INSTRUCTION

HP67/97

TITLE Efficiency of Grate Inlets PAGE 1 OF 3

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Input			
	Total gutter discharge	Q_T	A	Q_T
	Longitudinal roadway slope	S_o	B	S_o
	Reciprocal of road cross slope	Z	C	Z
	Width of grate	W	D	W
	Length of grate	L	E	L
2	Input coefficients			
		m	a	m
		k	b	k
		a	c	a
		c	d	c
3	Compute hydraulic efficiency		e	E

REGISTERS

0	1 Q_T	2 S_o	3 Z	4 W	5 L	6 m	7 k	8 a	9 c
S0 E	S1	S2	S3	S4	S5	S6	S7	S8	S9

A y_1	B y_2	C L_o	D L_c	E E	I

TITLE Efficiency of Grate Inlets PAGE 2 OF 3 HP67/97 Coding

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11		051	RCL2	36 02	
2	STO1	35 01		2	·	-62	
3	RTN	24		3	6	06	
4	*LBLB	21 12		4	5	05	
5	STO2	35 02		5	y^x	31	
6	RTN	24		6	x	-35	
7	*LBLC	21 13		7	RCLB	36 12	
8	STO3	35 03		8	1	01	
9	RTN	24		9	·	-62	
010	*LBLD	21 14		060	1	01	
1	STO4	35 04		1	7	07	
2	RTN	24		2	y^x	31	
3	*LBLE	21 15		3	x	-35	
4	STO5	35 05		4	RCL3	36 03	
5	RTN	24		5	x	-35	
6	*LBLa	21 16 11		6	STOC	35 13	
7	STO6	35 06		7	RCL9	36 09	
8	RTN	24		8	RCL1	36 01	
9	*LBLb	21 16 12		9	RCL2	36 02	
020	STO7	35 07		070	x	-35	
1	RTN	24		1	RCL3	36 03	
2	*LBLc	21 16 13		2	÷	-24	
3	STO8	35 08		3	·	-62	
4	RTN	24		4	6	06	
5	*LBLd	21 16 14		5	7	07	
6	STO9	35 09		6	y^x	31	
7	RTN	24		7	x	-35	
8	*LBLe	21 16 15		8	STOD	35 14	
9	RCL1	36 01		9	1	01	
030	RCL6	36 06		080	ENT↑	-21	
1	÷	-24		1	RCLB	36 12	
2	RCL2	36 02		2	RCLA	36 11	
3	$\sqrt{x}$	54		3	÷	-24	
4	÷	-24		4	2	02	
5	RCL3	36 03		5	·	-62	
6	÷	-24		6	6	06	
7	·	-62		7	7	07	
8	3	03		8	STO0	35 00	
9	7	07		9	y^x	31	
040	5	05		090	RCL5	36 05	
1	y^x	31		1	RCLC	36 13	
2	STOA	35 11		2	÷	-24	
3	RCL4	36 04		3	RCL8	36 08	
4	RCL3	36 03		4	y^x	31	
5	÷	-24		5	CHS	-22	
6	−	-45		6	1	01	
7	STOB	35 12		7	+	-55	
8	x<0?	16-45		8	x<0?	16-45	
9	GTO3	22 03		9	GTO3	22 03	
050	RCL7	36 07		100	RCL0	36 00	

TITLE Efficiency of Grate Inlets PAGE 3 OF 3 HP 67/97 Coding

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
101	y^x	31		151	CHS	-22	
2	x	-35		2	RCLE	36 15	
3	-	-45		3	+	-55	
4	STOE	35 15		4	RTN	24	
5	RCL5	36 05		5	*LBL2	21 02	
6	RCLD	36 14		6	ENT↑	-21	
7	÷	-24		7	ENT↑	-21	
8	1	01		8	RCL0	36 00	
9	x>y?	16-34		9	y^x	31	
110	GTO1	22 01		160	CHS	-22	
1	0	00		1	1	01	
2	P⇄S	16-51		2	+	-55	
3	STO0	35 00		3	x⇄y	-41	
4	P⇄S	16-51		4	1	01	
5	RCLE	36 15		5	+	-55	
6	RTN	24		6	R↑	16-31	
7	*LBL1	21 01		7	2	02	
8	x⇄y	-41		8	x	-35	
9	·	-62		9	x⇄y	-41	
120	5	05		170	÷	-24	
1	6	06		1	CHS	-22	
2	y^x	31		2	1	01	
3	RCLB	36 12		3	+	-55	
4	RCLA	36 11		4	x	-35	
5	÷	-24		5	P⇄S	16-51	
6	x>y?	16-34		6	STO0	35 00	
7	GTO2	22 02		7	P⇄S	16-51	
8	ENT↑	-21		8	CHS	-22	
9	ENT↑	-21		9	RCLE	36 15	
130	RCL0	36 00		180	+	-55	
1	y^x	31		1	RTN	24	
2	CHS	-22		2	*LBL3	21 03	
3	1	01		3	0	00	
4	+	-55		4	P⇄S	16-51	
5	x⇄y	-41		5	STO0	35 00	
6	ENT↑	-21		6	P⇄S	16-51	
7	x	-35		7	1	01	
8	CHS	-22		8	STOE	35 15	
9	1	01		9	RTN	24	
140	+	-55		190	R/S	51	
1	÷	-24					
2	1	01					
3	R↑	16-31					
4	-	-45					
5	ENT↑	-21					
6	x	-35					
7	x	-35					
8	P⇄S	16-51					
9	STO0	35 00					
150	P⇄S	16-51					

B. Discharge of Grate in a Sump Condition

Input and output parameters of all programs for computing discharges for the three grates in a sump condition are as follows:

Input Data:

Z - reciprocal of roadway cross slope
W - width of grate
L - length of grate
h - height of curb opening
p - coefficient for orifice discharge
q - exponent for orifice discharge coefficient
y_1 - sump depth at the curb

Output:

y_1 - sump depth at the curb
Q_w or Q_o - sump discharge

The following examples may be used to test these programs for discharge of grate inlets in a sump condition:

Z	W	L	h	p	q	y_1	Q
24	1.5	1.5	0.333	0.34	0.8	0.3	1.974
16	1.5	3.0	↓	0.34	0.8	0.5	5.553
16	1.5	1.5		0.30	0.7	0.8	7.346
24	3.0	3.0		0.30	0.7	1.0	23.93
48	1.5	3.0		0.32	0.25	1.2	14.71

```
C     THIS PROGRAM COMPUTES SUMP GRATE DISCHARGE
      READ(5,1)Z,W,AL,H,CP,CQ,Y1
1     FORMAT(7F7.3)
      Y2=Y1-W/Z
      IF(Y2.LT.0.)Y2=0.
      Y=Y1+Y2
C     CHECK IF WEIR OR ORIFICE FLOW
      A=Y1-0.43*AL**0.7
      IF(A.GT.0.)GO TO 10
C     WEIR FLOW
      Q=3.5*((AL-Y2)*Y2**1.5+0.707*W*Y**1.5)
      GO TO 12
C     ORIFICE FLOW
10    CG=(CP*Y**CQ)/(AL**0.5)
      Q=0.7*AL*H*(64.4*(Y1-H/2.))**0.5+CG*W*AL*(32.2*Y)**0.5
12    WRITE(6,2)Y1,Q
2     FORMAT(10X,4HY1 =,F6.3,5X,11HDISCHARGE =,F8.3)
      STOP
      END
```

TITLE Sump Grate Discharge PAGE 1 OF 3

PROGRAMMER ______ DATE ______

TI Programmable
Program Record

Partitioning (Op 17) ______ Library Module ______ Printer ______ Cards ______

PROGRAM DESCRIPTION

TI 58/59

This program is to compute discharges of the three bicycle-safe grates(P-1-1/8, P-1-7/8-4, and Curved Vane) in a sump condition. The formulas to be used are listed in Tables 1 and 2 in the manual. Correct coefficients must be used.

Note: If the TI-58 is used, printing instructions should be ignored.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Input:					
	Reciprocal of road cross slope	Z	A			Z
	Grate width	W	B			W
	Grate length	L	C			L
	Height of curb opening	h	D			h
2	Input Coefficients:					
	Coefficient for orifice discharge	p	E			p
	Exponent for orifice discharge	q	2nd	A		q
3	Enter water depth at sump	y_1	2nd	B		y_1
4	Start computation		2nd	C		Discharge, Q
5	Repeat steps 3 and 4 for other sump depths					

USER DEFINED KEYS	
A	Z
B	W
C	L
D	h
E	p
A'	q
B'	
C'	
D'	
E'	

DATA REGISTERS (INV ■)

0		10	$0.43L^{0.7}$
1	Z	11	$y_1-0.43L^{0.7}$
2	W	12	Q
3	L	3	
4	h	4	
5	p	5	
6	q	6	
7	y_1	7	
8	y_2	8	
9	y_1+y_2	9	

LABELS (Op 08)

INV lnx CE CLR x⇄t x²
√x 1/x STO RCL SUM yˣ
EE ( ) ÷ GTO ×
SBR − RST + R/S .
+/- = CLR INV

FLAGS										
	0	1	2	3	4	5	6	7	8	9

TITLE Sump Grate Discharge PAGE 2 OF 3

PROGRAMMER ________ DATE ________

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
0	76	Lbl	
	11	A	
	42	STO	
	01	01	
	91	R/S	
	76	Lbl	
	12	B	
	42	STO	
	02	02	
	91	R/S	
10	76	Lbl	
	13	C	
	42	STO	
	03	03	
	91	R/S	
	76	Lbl	
	14	D	
	42	STO	
	04	04	
	91	R/S	
20	76	Lbl	
	15	E	
	42	STO	
	05	05	
	91	R/S	
	76	Lbl	
	16	A'	
	42	STO	
	06	06	
	91	R/S	
30	76	Lbl	
	17	B'	
	42	STO	
	07	07	
	91	R/S	
	71	Lbl	
	18	C'	
	43	RCL	
	07	07	
	75	−	
40	43	RCL	
	02	02	
	55	÷	
	43	RCL	
	01	01	
	95	=	
	42	STO	
	08	08	
	22	INV	
	77	GE	
50	38	SIN	
	76	Lbl	
	85	+	
	43	RCL	
	08	08	

LOC	CODE	KEY	COMMENTS
55	85	+	
	43	RCL	
	07	07	
	95	=	
	42	STO	
60	09	09	
	43	RCL	
	07	07	
	75	−	
	53	(	
	93	.	
	04	4	
	03	3	
	65	x	
	43	RCL	
70	03	03	
	45	y^x	
	93	.	
	07	7	
	54	)	
	42	STO	
	10	10	
	95	=	
	42	STO	
	11	11	
80	77	GE	
	24	CE	
	03	3	
	93	.	
	05	5	
	65	x	
	53	(	
	53	(	
	43	RCL	
	03	03	
90	75	−	
	43	RCL	
	08	08	
	54	)	
	65	x	
	43	RCL	
	08	08	
	45	y^x	
	01	1	
	93	.	
100	05	5	
	85	+	
	93	.	
	07	7	
	00	0	
	07	7	
	65	x	
	43	RCL	
	02	02	
	65	x	

LOC	CODE	KEY	COMMENTS
110	43	RCL	
	09	09	
	45	y^x	
	01	1	
	93	.	
	05	5	
	54	)	
	95	=	
	42	STO	
	12	12	
120	61	GTO	
	49	Prd	
	91	R/S	
	76	Lbl	
	24	CE	
	43	RCL	
	05	05	
	65	x	
	43	RCL	
	09	09	
130	45	y^x	
	43	RCL	
	06	06	
	55	÷	
	43	RCL	
	03	03	
	34	$\sqrt{x}$	
	65	x	
	43	RCL	
	02	02	
140	65	x	
	43	RCL	
	03	03	
	65	x	
	53	(	
	03	3	
	02	2	
	93	.	
	02	2	
	65	x	
150	43	RCL	
	09	09	
	54	)	
	34	$\sqrt{x}$	
	85	+	
	93	.	
	07	7	
	65	x	
	43	RCL	
	03	03	

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

TITLE Sump Grate Discharge PAGE 3 OF 3

PROGRAMMER DATE

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
160	65	x		215	04	4	TI 59 only
1	43	RCL		6	69	Op	↓
2	04	04		7	04	04	
3	65	x		8	43	RCL	
4	53	(		9	12	12	
5	06	6		220	69	Op	TI 59
6	04	4		1	06	06	only
7	93	.		2	91	R/S	
8	04	4		3	76	Lbl	
9	65	x		4	38	SIN	
170	53	(		5	25	CLR	
1	43	RCL		6	42	STO	
2	07	07		7	08	08	
3	75	-		8	69	Op	TI 59
4	43	RCL		9	00	00	only
5	04	04		230	00	0	↓
6	55	÷		1	00	0	
7	02	2		2	04	4	
8	54	)		3	05	5	
9	54	)		4	00	0	
180	34	√x		5	03	3	
1	95	=		6	00	0	
2	42	STO		7	00	0	
3	12	12		8	02	2	
4	76	Lbl		9	04	4	
5	49	Prd		240	69	Op	
6	06	6	TI 59	1	01	01	
7	04	4	only	2	03	3	
8	04	4	↓	3	06	6	
9	05	5		4	00	0	
190	00	0		5	00	0	
1	02	2		6	03	3	
2	69	Op		7	01	1	
3	04	04		8	01	1	
4	43	RCL		9	07	7	
5	07	07		250	02	2	
6	69	Op		1	02	2	
7	06	06		2	69	Op	
8	06	6		3	02	02	
9	04	4		4	69	Op	
200	01	1		5	05	05	↓
1	05	5		6	61	GTO	
2	02	2		7	85	+	
3	03	3		8	92	RTN	
4	02	2		9			
5	06	6		0			
6	69	Op		1			
7	04	04		2			
8	43	RCL		3			
9	10	10		4			
210	69	Op		5			
1	06	06		6			
2	06	6		7			
3	04	4		8			
4	03	3	↓	9			

LOC	CODE	KEY	COMMENTS
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
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5			
6			
7			
8			
9			

MERGED CODES

62 ■ ■	72 STO ■	83 GTO ■
63 ■ ■	73 RCL ■	84 ■ ■
64 ■ ■	74 SUM ■	92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

USER INSTRUCTIONS

HP67/97

TITLE Sump Grate Discharge PAGE 1 OF 3

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Input:			
	Reciprocal of roadway cross			
	slope	Z	A	Z
	Grate width	W	B	W
	Grate length	L	C	L
	Height of curb opening	h	D	h
2	Input Coefficients:			
	Coefficient for orifice discharge	p	E	p
	Exponent for orifice discharge			
	coefficient	q	a	q
3	Enter water depth at sump	y_1	b	y_1
4	Compute discharge		c	Q
5	Repeat Steps 3 and 4 for other			
	depths			

REGISTERS

0	1 Z	2 W	3 L	4 h	5 p	6 q	7 y_1	8 y_2	9 y_1+y_2
S0	S1	S2	S3	S4	S5	S6	S7	S7	S9

A	B	C	D	E	I

TITLE Sump Grate Discharge PAGE 2 OF 3 HP67/97 Coding

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11		051	STOA	35 11	
2	STO1	35 01		2	RCL3	36 03	
3	*LBLB	21 12		3	RCL8	36 08	
4	STO2	35 02		4	−	-45	
5	RTN	24		5	RCL8	36 08	
6	*LBLC	21 13		6	1	01	
7	STO3	35 03		7	.	-62	
8	RTN	24		8	5	05	
9	*LBLD	21 14		9	y^x	31	
010	STO4	35 04		060	x	-35	
1	RTN	24		1	.	-62	
2	*LBLE	21 15		2	7	07	
3	STO5	35 05		3	0	00	
4	RTN	24		4	7	07	
5	*LBLa	21 16 11		5	RCL2	36 02	
6	STO6	35 06		6	x	-35	
7	RTN	24		7	RCL9	36 09	
8	*LBLb	21 16 12		8	1	01	
9	STO7	35 07		9	.	-62	
020	RTN	24		070	5	05	
1	*LBLc	21 16 13		1	y^x	31	
2	RCL7	36 07		2	x	-35	
3	RCL2	36 02		3	+	-55	
4	RCL1	36 01		4	RCLA	36 11	
5	÷	-24		5	x	-35	
6	−	-45		6	STOE	35 15	
7	0	00		7	GTO3	22 03	
8	x≠y	-41		8	*LBL2	21 02	
9	x≤y?	16 16-35		9	3	03	
030	x≠y	-41		080	2	02	
1	STO8	35 08		1	.	-62	
2	RCL7	36 07		2	2	02	
3	+	-55		3	STOB	35 12	
4	STO9	35 09		4	RCL5	36 05	
5	.	-62		5	RCL9	36 09	
6	4	04		6	RCL6	36 06	
7	3	03		7	y^x	31	
8	RCL3	36 03		8	x	-35	
9	.	-62		9	RCL3	36 03	
040	7	07		090	$\sqrt{x}$	54	
1	y^x	31		1	÷	-24	
2	x	-35		2	STOC	35 13	
3	STO0	35 00		3	RCL3	36 03	
4	RCL7	36 07		4	RCL4	36 04	
5	x>y?	16-34		5	x	-35	
6	GTO2	22 02		6	.	-62	
7	*LBL1	21 01		7	7	07	
8	3	03		8	x	-35	
9	.	-62		9	STOD	35 14	
050	5	05		100	2	02	

TITLE Sump Grate Discharge (continued) PAGE 3 OF 3 HP67/97 Coding

STEP	KEY ENTRY	KEY CODE	COMMENTS
101	RCLB	36 12	
2	x	-35	
3	RCL7	36 07	
4	RCL4	36 04	
5	2	02	
6	÷	-24	
7	-	-45	
8	x	-35	
9	√x	54	
110	RCLD	36 14	
1	x	-35	
2	RCLC	36 13	
3	RCL2	36 02	
4	RCL3	36 03	
5	x	-35	
6	x	-35	
7	RCLB	36 12	
8	RCL9	36 09	
9	x	-35	
120	√x	54	
1	x	-35	
2	+	-55	
3	STOE	35 15	
4	*LBL3	21 03	
5	RCLE	36 15	
6	RTN	24	
7	R/S	51	

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

2 Burgi, P.H., "Bicycle-Safe Grate Inlets Study. Volume 2 - Hydraulic Characteristics of Three Selected Grate Inlets on Continuous Grades," Federal Highway Administration, Report No. FHWA-RD-78-4, May 1978.

3 Burgi, P.H., "Bicycle-Safe Grate Inlets Study. Volume 3 - Hydraulic Characteristics of Three Selected Grate Inlets in a Sump Condition," Federal Highway Administration, Report No. FHWA-RD-78-70, September 1978.

4 Izzard, Carl F., "Hydraulics of Runoff from Developed Surface," Highway Research Board, Vol. 26, 1946.

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5 Li, W.H., "The Design of Storm-Water Inlets," Department of Sanitary Engineering and Water Resources, Johns Hopkins University, June 1956.

6 Davis, C.V., Handbook of Applied Hydraulics, McGraw-Hill Co., 1952.

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APPENDIX

ANALYSIS OF FLOW AT A GRATE INLET

I. Grates on a Continuous Grade

Gutter flow at a grate inlet is generally divided into two parts: (1) frontal flow that directly passes over the upstream edge of the grate and (2) the remaining part generally called side flow. Varying portions of these flows will be intercepted by the grate depending on the flow condition, the geometry of the road and the type of grate inlet.

The hydraulic efficiency, E, of a grate is defined as the ratio of the flow intercepted, Q_i, to the total gutter flow, Q_T,

$$E = Q_i/Q_T \qquad \text{(A-1)}$$

This can also be expressed in terms of the portion of the flow which is not intercepted:

$$E = 1 - R_s - R_f \qquad \text{(A-2)}$$

where

R_s = ratio of unintercepted side flow to the total gutter flow
R_f = ratio of unintercepted frontal flow to the total gutter flow.

A. Side Flow

A typical flow pattern of gutter flow at a grate inlet is shown in Figure 4. The side flow, designated with subscript 2, is subject to a lateral motion as the portion of the frontal flow is drained and the water surface drawn down. Because of this lateral motion, the side flow curves toward the grate, and the flow near the grate will be intercepted by the grate. Assuming a constant lateral acceleration, Li (5) found that the flow line at a curb inlet formed a parabolic curve. A similar flow pattern prevails for the side flow at a grate inlet. However, the curve is expected to be milder because the resistance of the grate tends to impede the lateral motion of the flow, thus pushing the flow downstream. In this study, a curve of "a"th power was assumed, i.e. the width, y_2Z, of the side flow is proportional to L_0 to the "a"th power, where L_0 is the distance from the upstream edge of the grate to the intersection of the water edge and the gutter line (see Figure 4). Then the ratio of the width of the portion of the side flow intercepted to the total width of the side flow becomes

$$\frac{y_2Z - y_3Z}{y_2Z} = (L/L_0)^a \qquad \text{or} \qquad 1 - y_3/y_2 = (L/L_0)^a \qquad \text{(A-3)}$$

where

y_2, y_3 = flow depths of side flow
Z = reciprocal of roadway cross slope
L = length of grate
L_o = distance from upstream edge of grate to intersection of side flow and gutter line (see Figure 4)
a = exponent for side flow curvature

With the integrated Manning equation for gutter flow,

$$Q_T = \frac{0.557}{n} Z \, S_o^{0.5} \, y_1^{2.67} \tag{A-4}$$

the ratio R_s of the unintercepted side flow to the total gutter flow can be expressed as

$$R_s = \left\{\frac{y_3}{y_1}\right\}^{2.67} \quad \text{or} \quad R_s = \left\{\frac{y_2}{y_1}\right\}^{2.67} \left\{\frac{y_3}{y_2}\right\}^{2.67} \tag{A-5}$$

When Eq. (A-3) is substituted into the above equation, the result is

$$R_s = \left\{\frac{y_2}{y_1}\right\}^{2.67} \left[1 - \left(\frac{L}{L_o}\right)^{a}\right]^{2.67} \tag{A-6}$$

According to Li's study (5) for curb inlets, for $Z \geq 8$,

$$L_o = 23.15 \, S_o^{0.5} \, y_1^{1.17} \, Z \tag{A-7}$$

In order to determine the value of the exponent a and of L_o for the three inlet grates, the data with low discharge (for which 100 percent of the frontal flow was intercepted) were selected. For these data, $R_f = 0$ and the hydraulic efficiency obtained in the testing can be expressed as

$$E = 1 - R_s = 1 - \left\{\frac{y_2}{y_1}\right\}^{2.67} \left[1 - \left(\frac{L}{L_o}\right)^{a}\right]^{2.67} \tag{A-8}$$

Regression analysis revealed that the value of the exponent a is 1.5 for the P-1-7/8-4 and the P-1-1/8 grates and 1.8 for the curved vane grate. The following equation for L_o was found most adequate for all three grates:

$$L_o = 65 \, S_o^{0.65} \, y_1^{1.17} \, Z \tag{A-9}$$

B. Frontal Flow:

For high velocity flows, some frontal flow may skip over the grate and be unintercepted. The drawdown, y_d, of the water surface in this case is less than the flow depth y_1 at the curb. If no change in the mean velocity of the frontal flow over the grate is assumed, then the ratio of the unintercepted frontal flow to the total frontal flow would be the ratio of the cross-sectional area $(A_1)'$ of the flow at the downstream edge of the grate to the cross-sectional area of the frontal flow at the upstream edge of the grate. The shape of the area $(A_1)'$ may be triangular or trapezoidal depending on the drawdown, y_d. For $y_d > y_2$, the shape is a triangle. For $y_d < y_2$, the shape is trapezoidal. The ratio of the unintercepted frontal flow to the total frontal flow for these cases is,

for $y_d/y_1 \geq y_2/y_1$

$$\text{Ratio} = \frac{(1 - y_d/y_1)^2}{1 - (y_2/y_1)^2} \qquad \text{(A-10a)}$$

or, for $y_d/y_1 < y_2/y_1$

$$\text{Ratio} = 1 - \frac{2(y_d/y_1)}{1 + (y_2/y_1)} \qquad \text{(A-10b)}$$

To investigate drawdown, y_d, photographs of all runs were carefully studied to find the cases in which the water surface just intersected the downstream edge of the grate. In these cases, y_d equals y_1 and the relationship between y_d and the other parameters can be determined. The analysis yielded the following equation for y_d:

$$y_d = \frac{1}{b}(L/S_o)^{0.56} \qquad \text{(A-11)}$$

where b = experimental coefficient.

The coefficient b was found to be 46 for the P-1-7/8-4 grate and 34 for both the P-1-1/8 grate and the curved vane grate. If 100 percent frontal flow interception is desired, then the length of the grate must be chosen so that the value of y_d equals flow depth y_1, which means that curve a-c of the frontal flow in Figure 4 diminishes just at the downstream edge of the grate. This length shall be referred to as the critical length, L_c, in this report. By using the Manning equation for gutter flow with $n = 0.016$, the depth of flow, y_1, in feet, can be expressed as

$$y_1 = \left(\frac{Q_T}{34.8\, S_o^{0.5}\, Z}\right)^{0.375} \qquad \text{(A-12)}$$

where Q_T = discharge in cfs.

When Eq. (A-11) is set equal to Eq. (A-12), the critical length L_c can be found:

$$L_c = c\,(Q_T S_o/Z)^{0.67} \qquad \text{(A-13)}$$

The value c is 85 for the P-1-7/8-4 grate and 50 for the P-1-1/8 and the curved vane grates.

By definition, $y_d = y_1$ for $L = L_c$; therefore, from Eq. (A-11), the following relation can be established:

$$y_d/y_1 = (L/L_c)^{0.56} \qquad \text{(A-14)}$$

Since the ratio of the frontal flow to the total gutter flow is $1 - (y_2/y_1)^{2.67}$, the ratio R_f of the unintercepted frontal flow to the total gutter flow can be derived from Eqs. (A-9), (A-10), and (A-14) as

for $y_2/y_1 \leq (L/L_c)^{0.56} < 1$,

$$R_f = \left[1 - (y_2/y_1)^{2.67}\right]\left[\frac{\left(1 - (L/L_c)^{0.56}\right)^2}{1 - (y_2/y_1)^2}\right] \qquad \text{(A-15)}$$

or, for $(L/L_c)^{0.56} < y_2/y_1 < 1$,

$$R_f = \left[1 - (y_2/y_1)^{2.67}\right]\left[1 - \frac{2(L/L_c)^{0.56}}{1 + (y_2/y_1)}\right] \qquad \text{(A-16)}$$

The term in the first bracket in the above equations is the ratio of the frontal flow to the total gutter flow, and the term in the second bracket represents the ratio of the unintercepted frontal flow to the total frontal flow. The ratio R_f is same as efficiency adjustment, ΔE, in Table 1.

II. Grates in a Sump Condition

Flow at a grate inlet in a sump condition can be analyzed as either weir flow or orifice flow depending on the depth of flow. The weir flow condition controls until the flow depth is sufficiently deep to submerge the grate. The general equations for weir flow and orifice flow can be found elsewhere (6). For gutter flow where a cross slope exists, however, these general equations must be modified. In addition, a curb opening is generally added along the entire length of a sump grate to provide extra protection against debris accumulation. Although this type of curb opening does not affect weir flow, the curb opening discharges a substantial portion of gutter flow when the water is deep and orifice flow prevails. Therefore, the discharge through the curb opening must be considered for orifice flow. With these considerations, the weir equation and the orifice equation can be modified and expressed as

$$Q_w = C_w \{(L - \Delta L)\ (y_2)^{1.5} + 0.707W(y_1 + y_2)^{1.5}\} \qquad \text{(A-17)}$$

and

$$Q_o = C_o A_o \{2g(y_1 - h/2)\}^{0.5} + C_g A_g \{g(y_1 + y_2)\}^{0.5} \qquad \text{(A-18)}$$

where

C_w = discharge coefficient of the weir

ΔL = adjustment of weir length accounting for the contraction of flow

C_o = discharge coefficient of curb inlet

h = height of curb opening

A_o = cross-sectional area of curb opening, h x L

C_g = discharge coefficient of grate inlet

A_g = gross cross-sectional area of grate, W x L

Q_w = weir discharge

Q_o = orifice discharge

The first term on the right side of Eq. (A-18) is the discharge through the curb opening, and the second term is the discharge through the grate inlet. If no curb opening is provided, the first term should be eliminated.

A. Grate Inlet in Weir Flow Condition:

For moderate or low flow, a weir flow condition prevails at a grate inlet, and Eq. (A-17) can be used to determine the discharge. Generally, the weir flow pattern is similar for all types of grates regardless of their configurations. Therefore, all grates of larger sizes, i.e. 2 ft by 4 ft (0.61 m by 1.22 m) and 3 ft by 4 ft (0.61 m by 1.22 m) were analyzed to determine the weir coefficient and to investigate simultaneously the weir length adjustment, ΔL, for Eq. (A-17). The analysis resulted in a weir coefficient of 3.5 and $\Delta L = y_2$ which adequately fit all the data. Later, these values were tested and found to be adequate for other grates of smaller size in the weir flow condition. Equation (A-17) may be rewritten as

$$Q_w = C_w\{(L - y_2)y_2{}^{1.5} + 0.707W(y_1 + y_2)^{1.5}\} \qquad \text{(A-19)}$$

B. Grate Inlet in Orifice Flow Condition:

While the effect of a curb opening located along the grate inlet can be ignored when the flow is in a weir flow condition, the discharge through the curb opening becomes a significant portion of the total intercepted flow when flow depth increases and orifice flow conditions develop. Analysis of data from curb opening tests revealed that the orifice coefficient for curb opening is 0.7 as was found in report FHWA-RD-78-70 (3). Next, in order to determine the orifice coefficient, C_o, for the three grates, the data of smaller grates with larger flow depths were analyzed, assuming that orifice flow conditions prevailed. The orifice coefficients were found to be a function of average flow depth $(y_1 + y_2)/2$ and the length of the grate:

$$C_g = p(y_1 + y_2)^q/L^{0.5} \qquad \text{(A-20)}$$

Values of Experimental Coefficients

	p		q
	English	SI	
P-1-7/8-4	0.34	0.49	0.8
P-1-1/8	0.30	0.38	0.7
Curved Vane	0.32	0.24	0.25

Next, in order to find the depth y_1 for which the orifice equation applies, discharges were computed by using Eq. (A-18) for the whole range of flow depths; a comparison was then made with actual data. A distinct deviation of the data from the equation was recognized for flows with shallow depths where weir flow existed. The minimum flow depth for which the orifice equation can be applied was determined from this analysis to be

$$y_1 = 0.43\ L^{0.7} \qquad \text{(A-21)}$$

In other words, for $y_1 \geq 0.43\ L^{0.7}$, orifice flow exists and Eq. (A-18) applies. For $y_1 < 0.43\ L^{0.7}$, Eq. (A-19) must be used.

III. Comparison of Results

The efficiencies of the three grates on a continuous grade were computed by using the equations developed from the analysis on the preceding pages. They are plotted against the measured data in Figures 10 to 12. Approximately, 90 percent of the points lie within an error range of 5 percent and all within a range of 10 percent. As expected, the errors are larger for grates of shorter length for which some frontal flow splashes over and is unintercepted.

The same data were used to evaluate the method of determining grate efficiency presented in FHWA Report TS-79-225 (7). The results are presented in Figures 13 to 15. Although most points (except a few points for lower efficiencies) lie within the error range of 10 percent, this method tends to overestimate the efficiencies. As for the validity of the discharges for the three grates in a sump condition, the computed discharges were compared with the measured discharges in Figure 16. Only 3 out of 230 points slightly exceed the 10 percent error limit.

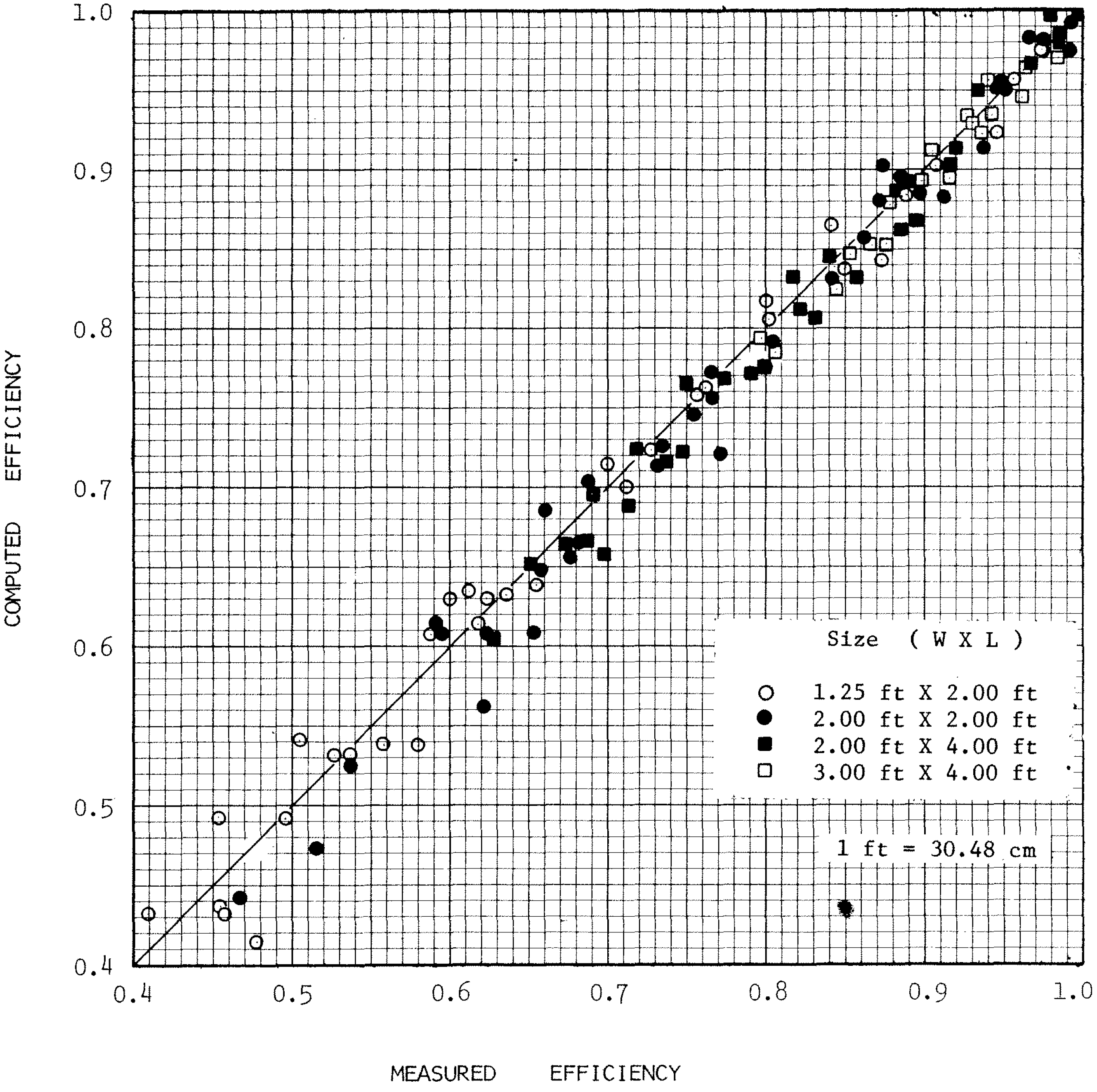

FIGURE 10 COMPARISON OF MEASURED AND COMPUTED EFFICIENCIES FOR P-1-7/8-4 GRATE

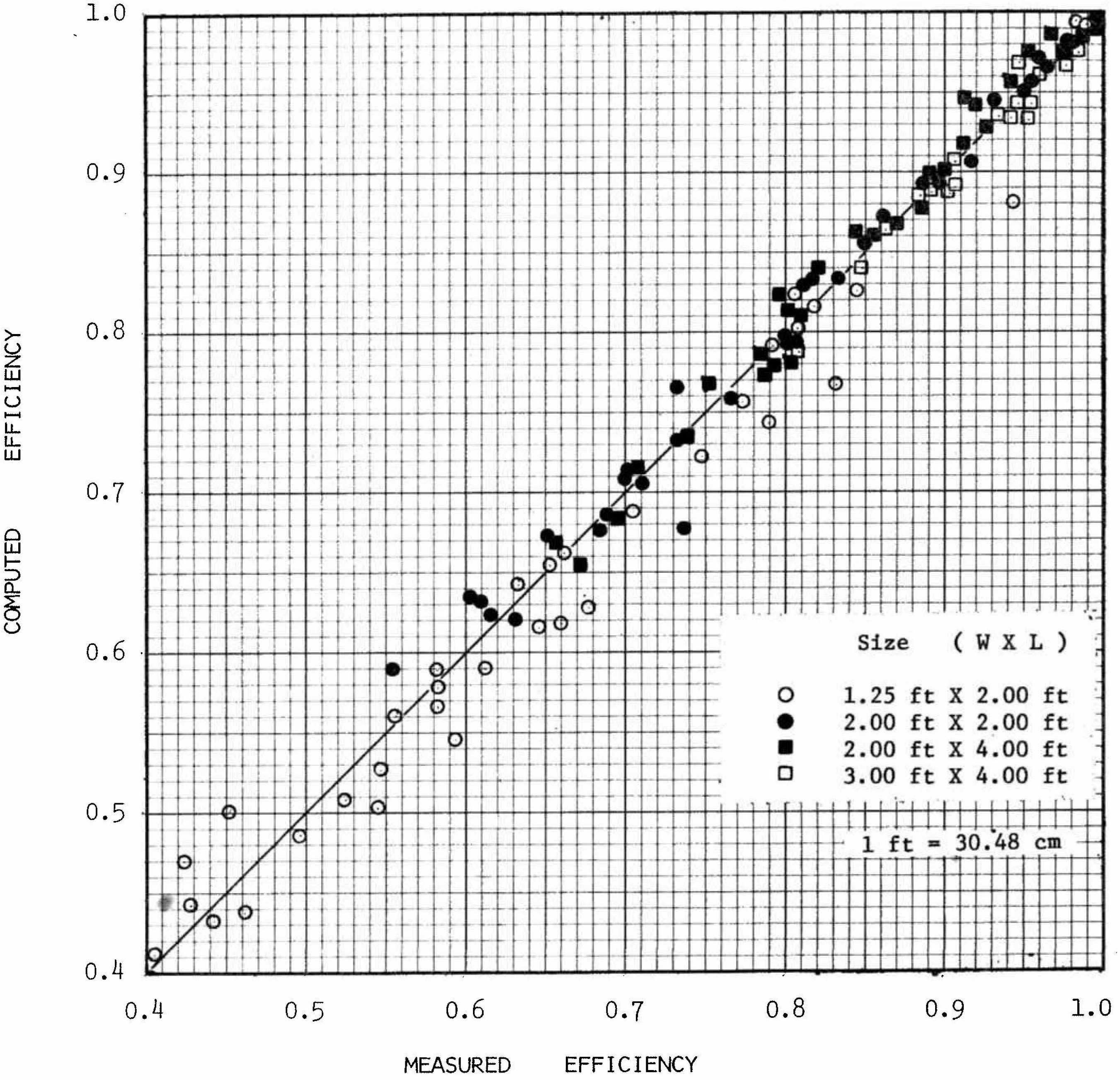

FIGURE 11 COMPARISON OF MEASURED AND COMPUTED EFFICIENCIES FOR P-1-1/8 GRATE

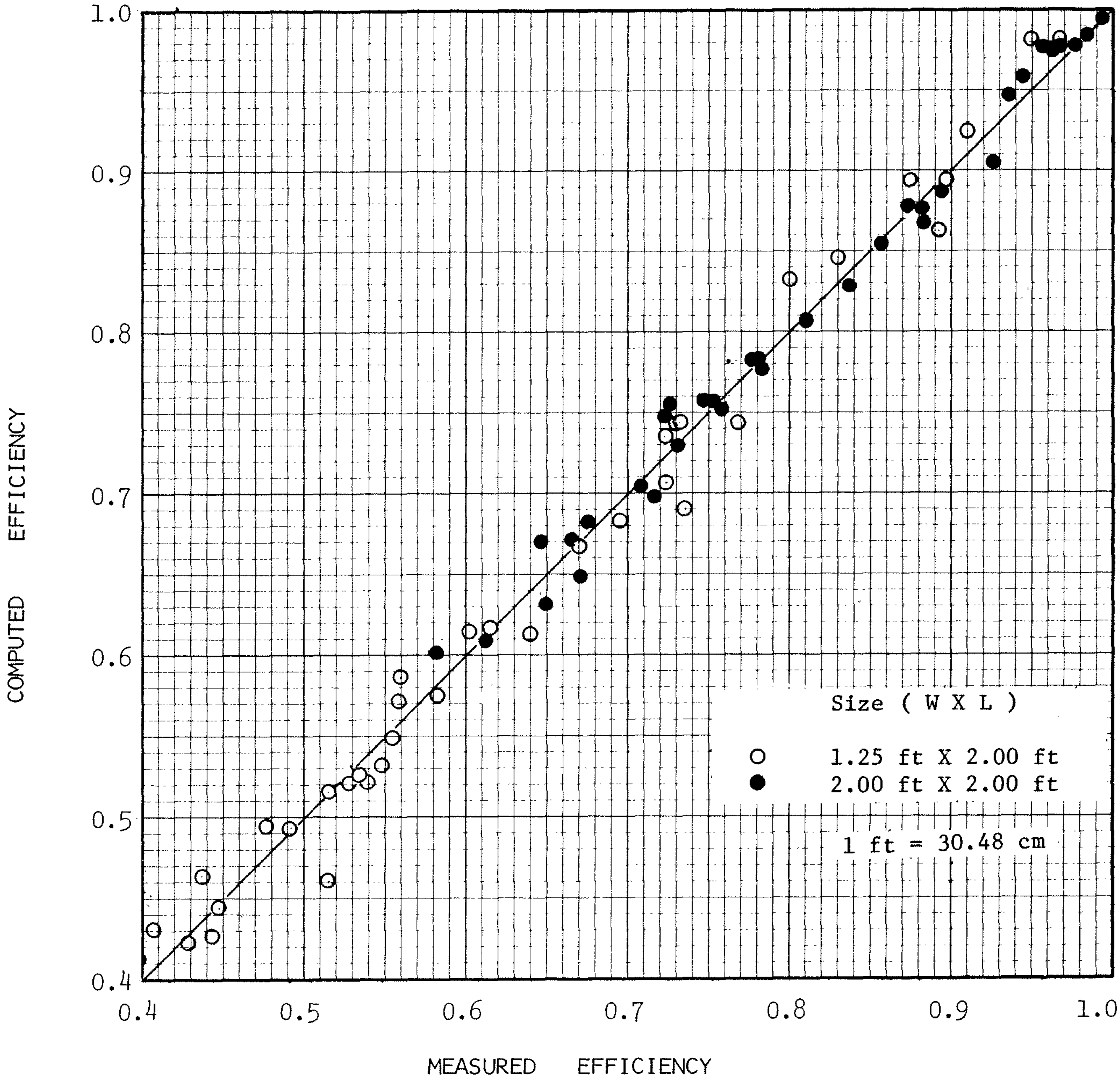

FIGURE 12 COMPARISON OF MEASURED AND COMPUTED EFFICIENCIES FOR CURVED VANE GRATE

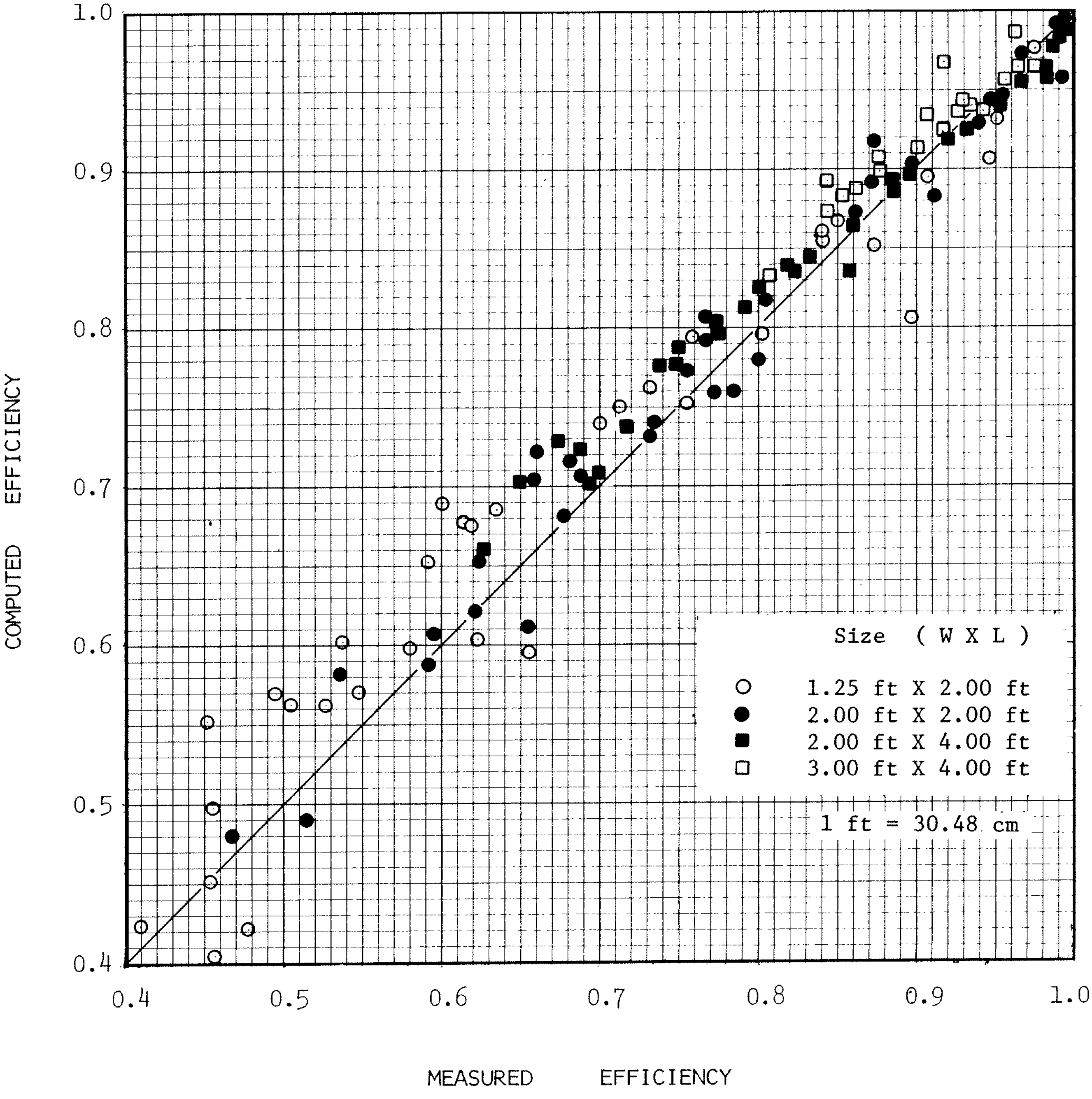

FIGURE 13 COMPARISON OF MEASURED EFFICIENCY AND COMPUTED EFFICIENCY BY USING FHWA-TS-79-225 METHOD, FOR P-1-7/8-4 GRATE

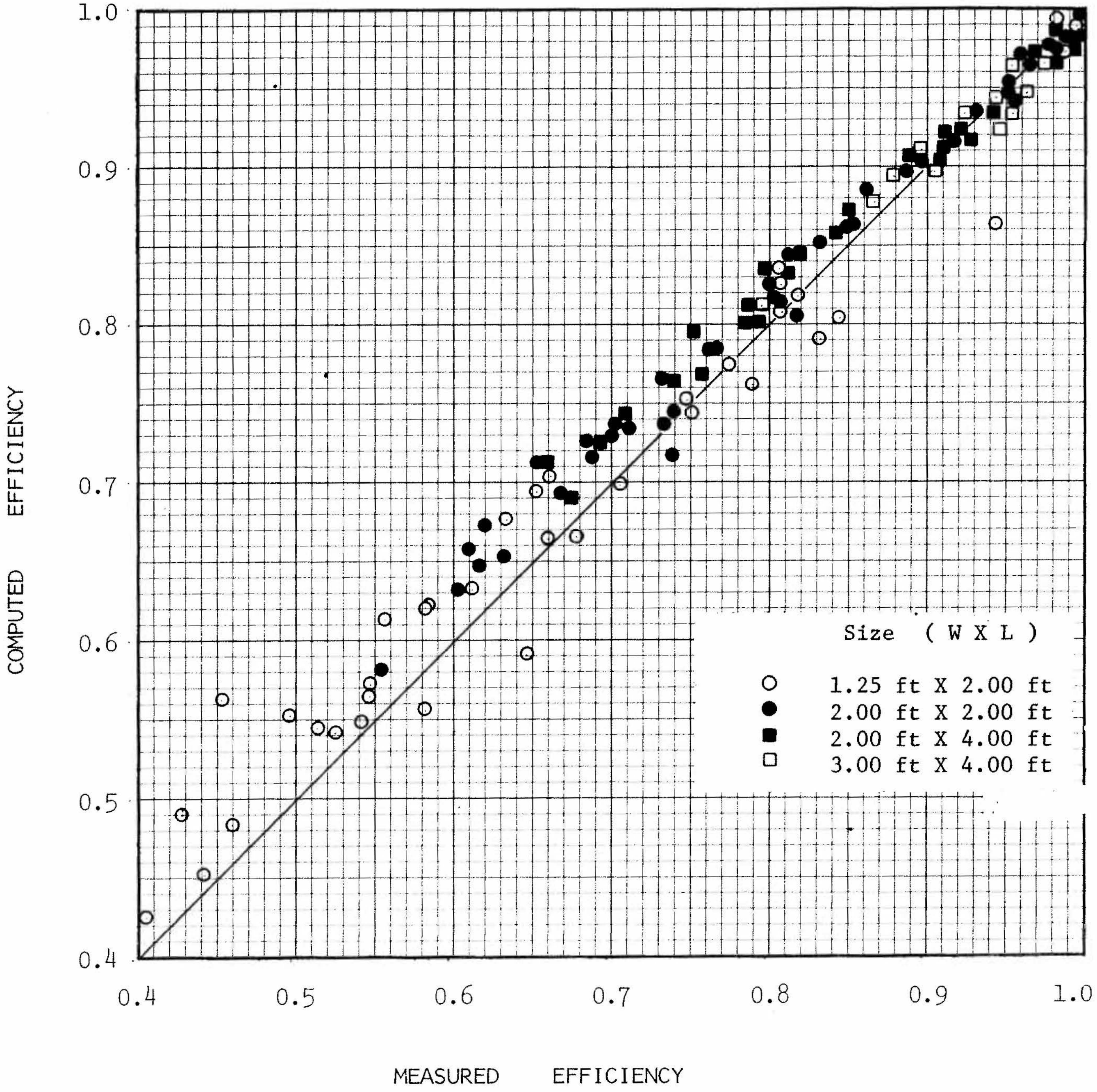

FIGURE 14 COMPARISON OF MEASURED EFFICIENCY AND COMPUTED EFFICIENCY BY USING FHWA-TS-79-225 METHOD FOR P-1-1/8 GRATE

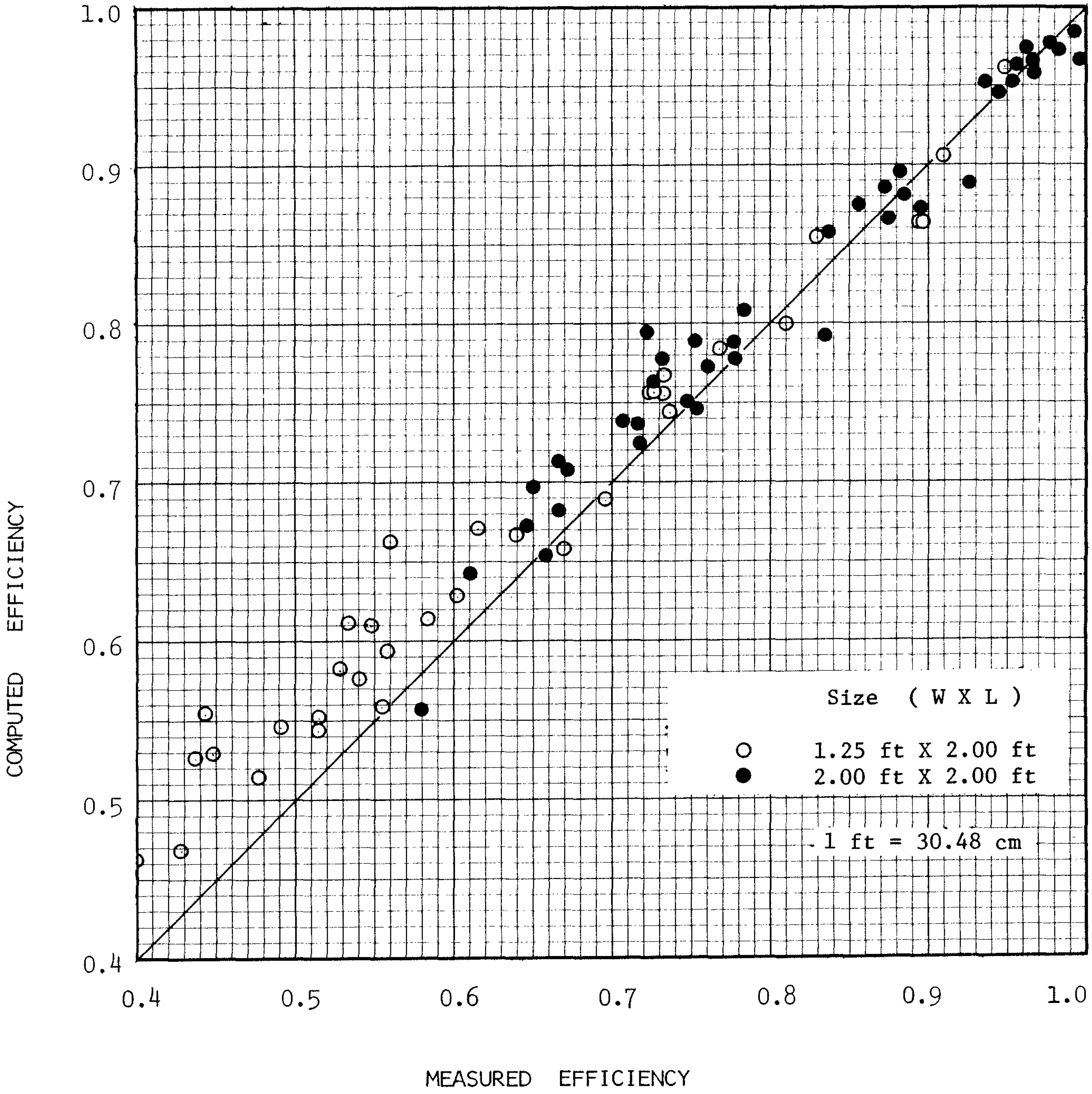

FIGURE 15 COMPARISON OF MEASURED EFFICIENCY AND COMPUTED EFFICIENCY BY USING FHWA-TS-79-225 METHOD FOR CURVED VANE GRATE

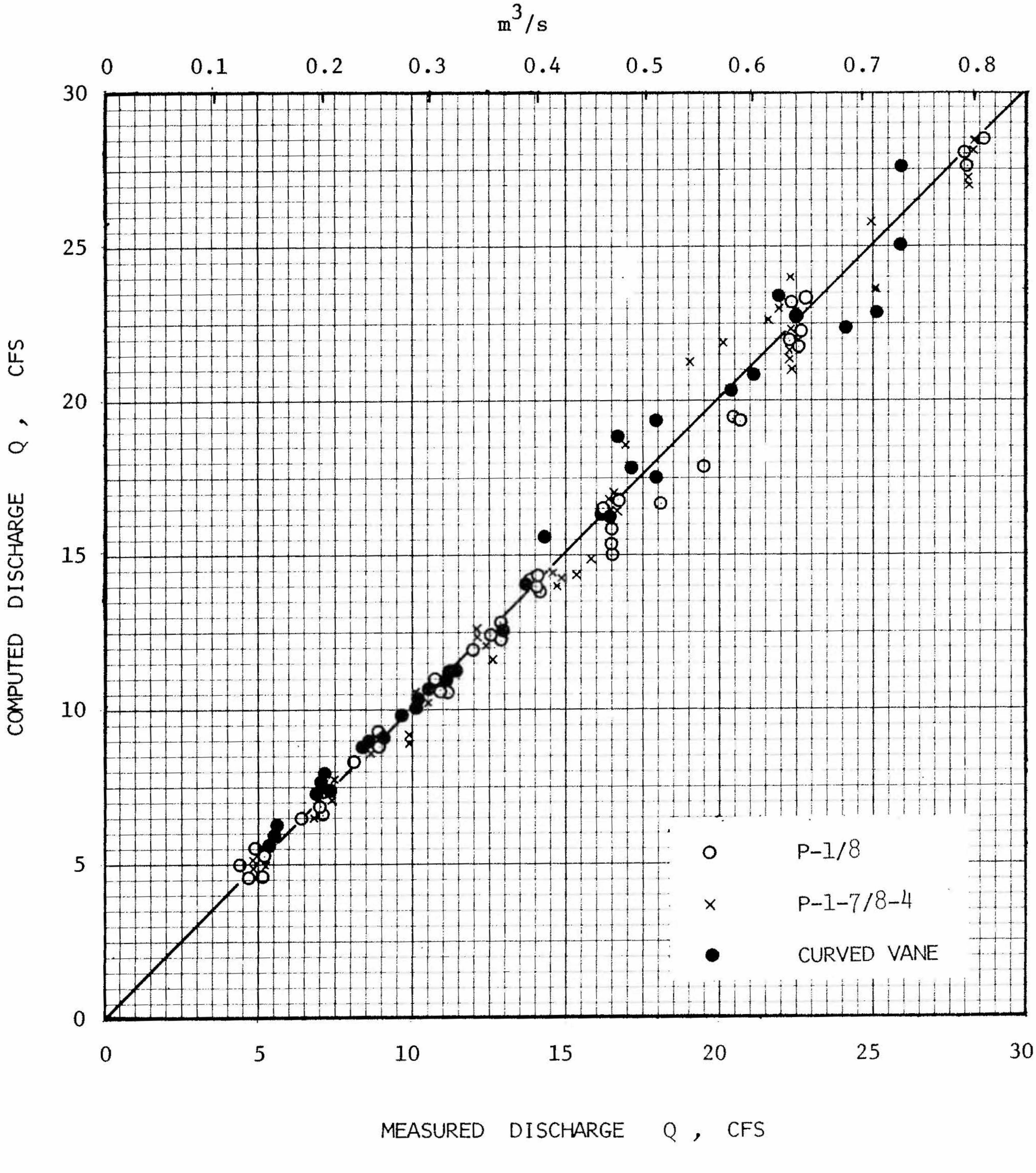

FIGURE 16 COMPARISON OF MEASURED AND COMPUTED DISCHARGES OF THE THREE GRATES IN A SUMP CONDITION

*U S GOVERNMENT PRINTING OFFICE: 1980 330-996/6722