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HYDRAULIC PERFORMANCE OF CURB AND GUTTER INLETS

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September 1999

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Hydraulic Performance of Curb and Gutter Inlets

by

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for

Kansas Department of Transportation

September 1999

PREFACE

This research project was funded by the Kansas Department of Transportation K-TRAN research program. The Kansas Transportation Research and New-Developments (K-TRAN) Research Program is an ongoing, cooperative and comprehensive research program addressing transportation needs of the State of Kansas utilizing academic and research resources from the Kansas Department of Transportation, Kansas State University and the University of Kansas. The projects included in the research program are jointly developed by transportation professionals in KDOT and the universities.

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ABSTRACT

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Proper drainage of the roadway is essential to highway safety. Drainage systems for roadways with curb and gutters are designed to limit spread of water on the pavement. Excess water must be captured by curb and gutter inlets. To locate and size these inlets properly, designers need reliable information on their hydraulic performance.

This report provides complete information on the hydraulic performance characteristics of KDOT's standard curb and gutter inlets on grade and in sag locations. It also provides design charts for the spread of water on roadways with curbs and gutters. The design charts for inlets on grade were developed from hydraulic model tests. The capacities of inlets in sag locations were computed from fundamental hydraulic principles.

2. KDOT CURB AND GUTTER INLETS

KDOT has four standard designs for curb and gutter inlets: the concrete gutter inlet, the Type B gutter inlet, the Type 12 combination inlet, and the Type 22 curb inlet. Figures 2.3 through 2.6 show the design features that are relevant to hydraulic performance. KDOT standard drawings show the complete designs of these inlets. The concrete gutter inlet is used on pavements with the KDOT standard gutter (Figure 2.1). The standard gutter is a 850-mm-wide shallow gutter with a flowline 40 mm below the edge of the pavement and an outer edge 40 mm above the edge of the pavement. The other three KDOT inlets are normally used on roadways with a Type I combined curb and gutter (Figure 2.2). The Type I curb and gutter is 750 mm wide. The flowline is 45 mm below the edge of the pavement and the top of the curb is 105 mm above the edge of the pavement.

The concrete gutter inlet (Figure 2.3) has a grated gutter opening 750 mm long (parallel to the edge of the pavement) and 700 mm wide. The opening is not depressed. The principal (top) bars of the grate are oriented longitudinally. The rectangular bars are 16 mm wide, and the clear openings between the bars are 48 mm wide.

The Type B gutter inlet (Figure 2.4) has a grated gutter opening 750 mm long and 450 mm wide. The opening is aligned with the gutter (not recessed) and is only slightly depressed (25 mm below the gutter). The principal bars of the grate are oriented longitudinally. The rectangular bars are 16 mm wide, and the clear openings between the bars are 32 mm wide.

The Type 12 combination inlet (Figure 2.5) has a grated gutter opening and a curb opening.

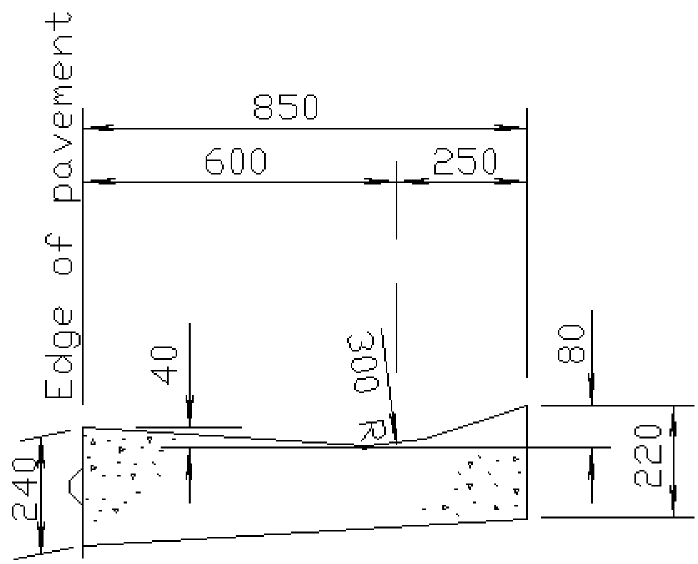


Fig. 1. Standard Gutter

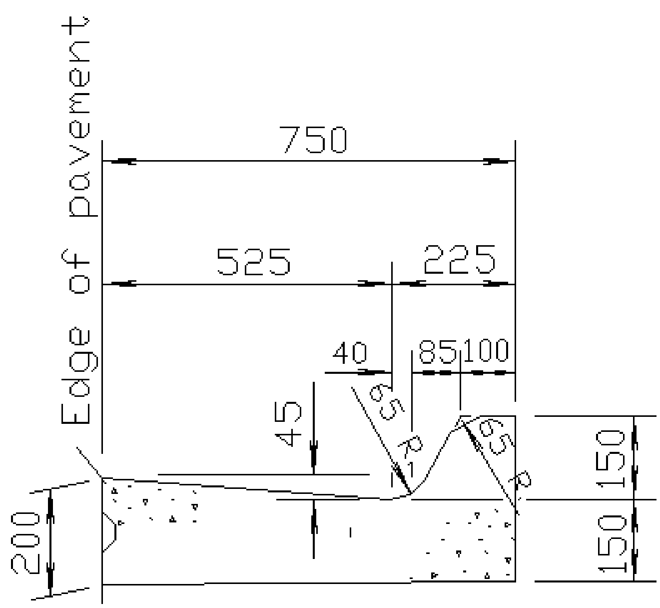
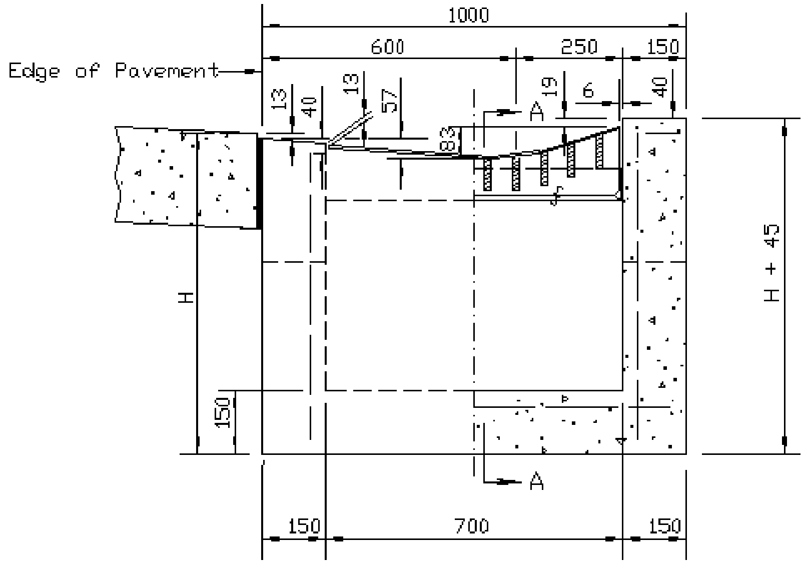
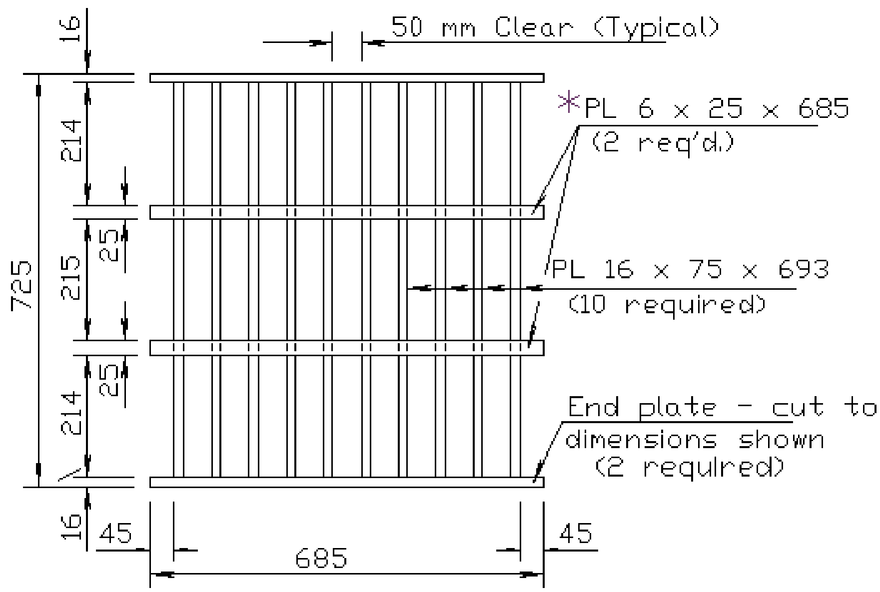


Fig. 2. Type I Combined Curb and Gutter

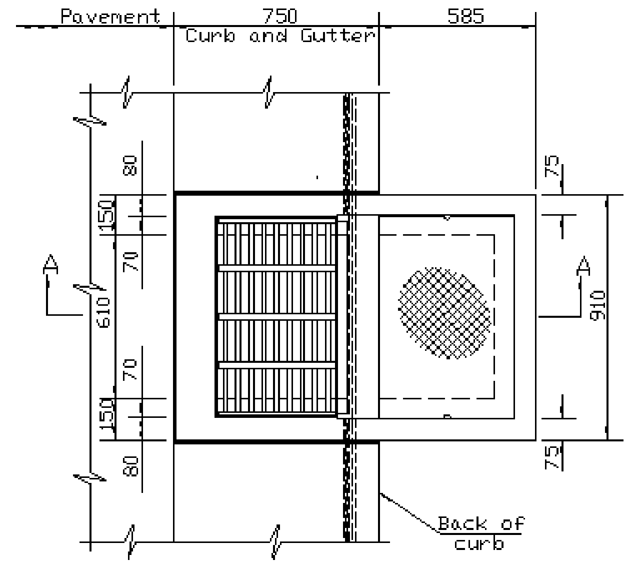


(a) Elevation

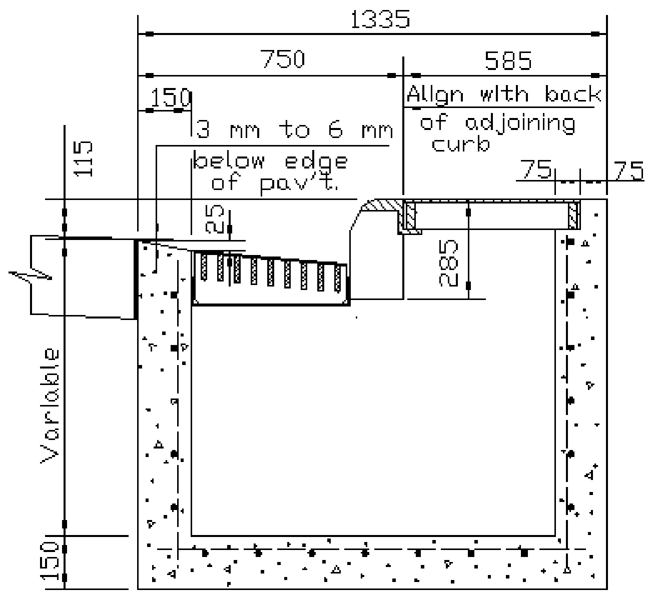


(b) Plan of Grate

Fig. 3. Concrete Gutter Inlet

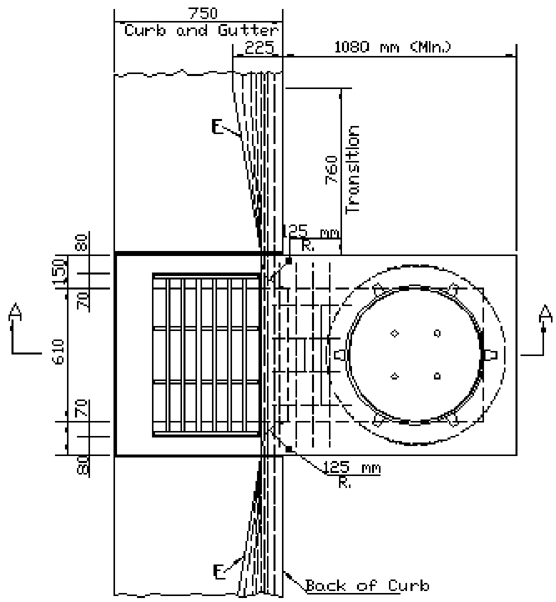


(a) Plan

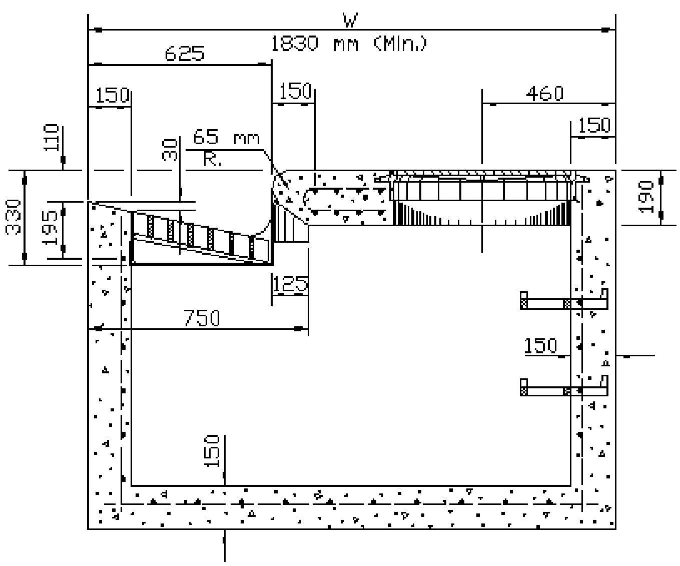


(b) Elevation (Section A-A)

Fig. 4. Type B Gutter Inlet

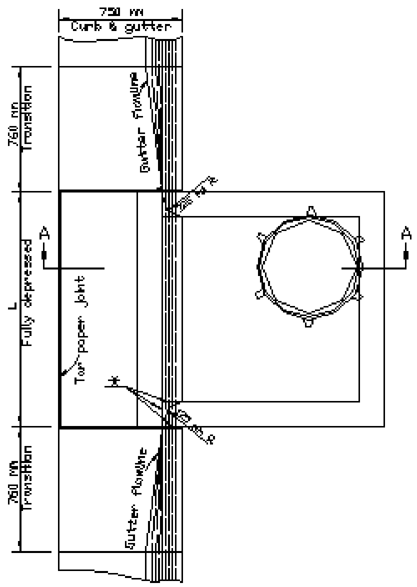


(a) Plan

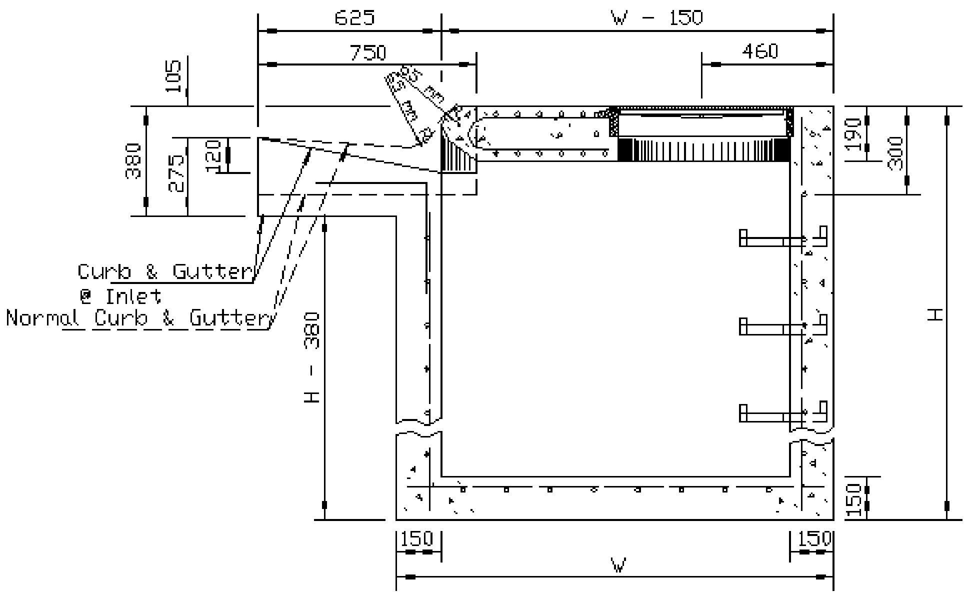


(b) Elevation (Section A-A)

Fig. 5. Type 12 Combination Inlet



(a) Plan



(b) Elevation (Section A-A)

Fig. 6. Type 22 Curb Inlet

These openings are depressed and recessed slightly. The gutter opening is 750 mm long and 475 mm wide. The principal bars of the grate are oriented longitudinally. The rectangular bars are 16 mm wide, and the clear openings between the bars are 54 mm wide. The curb opening is 750 mm long.

The Type 22 curb inlet (Figure 2.6) has a curb opening that is depressed and recessed slightly and no gutter opening. The three standard lengths of Type 22 inlets are 1.5 m, 3.0 m and 4.5 m. These dimensions are the lengths of concrete box structures. The corresponding lengths of the curb openings are 1.2 m, 2.7 m and 4.3 m.

3. HYDRAULIC PERFORMANCE OF INLETS ON GRADE

3.1 Experimental Set-Up

The hydraulic model studies of the KDOT standard inlets were conducted in the hydraulics laboratory at the University of Kansas. One-quarter-scale models of the inlets were constructed and tested on a 15-m-long model of a section of roadway. This apparatus was built in 1997 to test the Overland Park set-back inlets in K-TRAN Project KU-98-3 (McEnroe and Wade, 1998). New one-quarter-scale curbs and gutters were constructed and installed on the model roadway. The KDOT standard gutter was installed one side, and a Type I combined curb and gutter on the other side. The model curbs, gutters, inlets and transitions were constructed of wood and plaster. The grade and cross-slope of the model roadway are adjustable. The downstream end of the supporting box beam is hinged to the floor of the laboratory. The grade of the roadway is adjusted by raising or lowering the upstream end of the beam with a chain hoist. The roadway can be tilted toward either curb at any desired cross-slope. The distance from the upper end of the roadway to the start of the inlet transition is 9 m. High-density polyurethane foam panels form the roadway surface. All surfaces are painted. A commercial non-skid product was mixed into the paint to increase the roughness of the surfaces.

Water is supplied by the recirculating system that serves the two large flumes in the hydraulics laboratory. A 64-mm flexible conduit delivers water to a stilling basin attached to the upstream end of the roadway. This line is fed from a constant-head tank on the roof of the laboratory. The discharge is controlled with a ball valve. The water spills out of the stilling basin into the gutter and roadway. The water captured by the inlet is directed to a wooden box with a 90° V-notch weir at the downstream end. The water that bypasses the inlet is directed to an identical weir box at the downstream end of the roadway. The captured and bypassed discharges are measured with these weirs. The water level in the each weir box is measured in a stilling well with a point gage. The corresponding discharge is computed from the well established head-discharge relationship for a 90° V-notch weir (Bos, 1989). Each weir box contain baffles that distribute the flow uniformly and minimize surface waves. Discharges at heads below 0.03 m (0.1 ft) are determined volumetrically with a graduated cylinder and a stopwatch. The outflows from the weir boxes are directed to a sump pit. Water is pumped continuously from the sump pit to the constant-head tank.

3.2 Test Program

We tested each inlet at all combinations of five grades and two cross-slopes. The five grades were 0.5%, 1%, 2%, 3% and 5%. The two cross-slopes were 1.6% (3/16 inch per foot) and 3.1% (3/8 inch per foot). At each setup, the objective was to determine the relationship between the captured discharge and the total discharge (the sum of the captured and bypassed discharges). Initially, flow was established at a discharge that was captured entirely. This discharge was measured at the weir box. The flow was then increased slightly. When the water levels in the weir boxes stabilized, the captured discharge and the bypassed discharge (if any) were measured. This process was repeated until the flow overtopped the curb upstream of the inlet.

3.3 Model-Prototype Relations

The flow pattern in the vicinity of an inlet is determined primarily by two factors: gravity and inertia. The turning of the flow into the inlet is driven by gravity and resisted by inertia. The Froude number is the dimensionless number that indicates the relative importance of gravity and inertia. Within the inlet itself, frictional resistance is relatively insignificant. At normal grades, the flow in the gutter and roadway is supercritical. Supercritical flow is controlled from upstream. Therefore, the flow pattern in the vicinity of the inlet depends on the velocity and depth in the gutter and roadway upstream of the inlet. Under normal conditions, the upstream flow in the gutter and roadway is approximately uniform, meaning that the gravitational driving force and the frictional resistance are approximately in balance.

Model-prototype relations for geometrically similar inlets can be developed from a dimensional analysis. The discharge captured by a model of a particular design depends primarily on the size of the model, the depth and velocity of the flow upstream of the inlet, and the density and specific weight of the fluid. This relationship can be expressed as

$$Q_c = f(L, y_o, V_o, \rho, \gamma) \quad (1)$$

in which Q_c is the captured discharge, L is a characteristic length dimension, y_o and V_o are the depth and velocity of uniform flow in the gutter and roadway upstream of the inlet, and and are the density and specific weight of the fluid. Dimensional analysis leads to the relationship

$$\frac{Q_c}{\sqrt{gL^5}} = f\left(\frac{y_o}{L}, \frac{V_o}{\sqrt{gL}}\right) \quad (2)$$

Geometric similarity requires equal values of y_o/L in the model and prototype. If the Froude numbers of the uniform flows are also equal, then the captured discharges are related as follows:

$$\frac{Q_{c,m}}{Q_{c,p}} = \left(\frac{L_m}{L_p}\right)^{5/2} \quad (3)$$

(Henderson, 1966) in which the subscripts m and p indicate model and prototype. This scaling law, which follows from Eq. 2, also applies to the total discharge, Q_t (the sum of the captured and bypassed discharges), provided that the same conditions are satisfied:

$$\frac{Q_{t,m}}{Q_{t,p}} = \left(\frac{L_m}{L_p}\right)^{5/2} \quad (4)$$

In our tests, the length ratio L_m/L_p was 1/4, and the discharge ratios $Q_{c,m}/Q_{c,p}$ and $Q_{t,m}/Q_{t,p}$ were 1/32.

3.4. Calibration of the Model

The model was calibrated by adjusting the roughness of the surface. The objective was to achieve equal Froude numbers in the model and prototype for uniform flows at geometrically scaled depths, so that discharges could be scaled with Eqs. 2 and 3. This condition is met when the Manning friction factors for the model and prototype, n_m and n_p, are related as follows (Henderson, 1966):

$$\frac{n_m}{n_p} = \left(\frac{L_m}{L_p}\right)^{1/6} \tag{5}$$

For a one-quarter-scale model, Eq. 5 requires that $n_m = 0.79\ n_p$. For full-scale gutters and roadways, Manning friction factors typically range from 0.013 to 0.016, depending on condition (Chow, 1959; FHWA, 1996). In the model calibration tests, a constant discharge was established and measured, and the cross-section of the flow (depth versus distance from edge of pavement) was measured at a location where the flow was approximately uniform. The Manning n for the model was computed from the measured quantities. In repeated tests, the Manning n value of the model was found to be 0.010, which corresponds to a prototype Manning n of 0.013. This equivalent prototype roughness is at the smooth end of the normal range. For inlet tests, a roadway roughness at the smooth end of the normal range is appropriately conservative. The smoother the surface, the higher the velocity in the gutter and roadway. For most inlets, a higher velocity in the gutter and roadway results in a smaller captured discharge.

3.5 Analysis of Experimental Data

The graphs in Appendix A show the relationships between the captured discharge and the total discharge from all of the tests. The plotted discharges are equivalent prototype discharges. These graphs show both the experimental data and the fitted “design curves” for each combination of inlet type, cross-slope and grade.

We found that relationship between captured discharge and total discharge for each set-up can be approximated satisfactorily by a two-parameter equation. For certain combinations of conditions, the data are fitted well by the equation

$$Q_c = \begin{cases} Q_t & \text{for } Q_t \le Q_o \\ Q_o - (Q_a - Q_o)\left\{1 - \exp\left[-\left(\dfrac{Q_t - Q_o}{Q_a - Q_o}\right)\right]\right\} & \text{for } Q_t > Q_o \end{cases} \tag{6}$$

with parameters Q_o and Q_a. For other combinations of conditions, the data are fitted well by the equation

$$Q_c = \begin{cases} Q_t & \text{for } Q_t \le Q_o \\ Q_t - (Q_t - Q_o)^k & \text{for } Q_t > Q_o \end{cases} \tag{7}$$

with parameters Q_o and k. In both equations, the parameter Q_o represents the largest discharge that is captured completely. In Eq. 6, the parameter Q_a represents the upper limit on the captured discharge, which is approached asymptotically with increasing total discharge.

We used Eqs. 6 and 7 to fit the design curves to the experimental results. In some cases, the design curve approximates the minimum performance of the inlet at any grade. In other cases, a separate design curve applies to each grade. The design curves are plotted without the experimental results in Appendix B. Table 1 shows the form of the equation and the values of the parameters for each design curve.

3.6 Comparisons of Inlet Performance on Grade

Comparisons of the experimental results for the various set-ups lead to the following observations:

1. The grade of the roadway has little effect on the performance of the three inlets with gutter openings (concrete gutter inlet, Type B gutter inlet and Type 12 combination inlet). The effect of grade is also insignificant for the 4.5-m Type 22 curb inlet. All of these inlets perform as well (or slightly better) on steep grades (up to 5%) as on mild grades (down to 0.5%).
2. The grade of the roadway does have a significant effect on performance of the 1.5-m Type 22

curb inlet. The effect of grade is also significant for the 3.0-m Type 22 inlet at the steeper cross-slope. These inlets perform better on mild grades than on steep grades.

3. On a grade of 0.5%, the 1.5-m Type 22 curb inlet performs as well as the Type 12 combination inlet and the Type B gutter inlet. On steeper grades, the Type 12 and Type B inlets perform better than the Type 22 inlet.
4. All of the inlets perform slightly better on the steeper cross-slope.
5. The performance characteristics of the concrete gutter inlet and the Type B gutter inlet are similar for all test conditions.
6. The Type 12 combination inlet performs slightly better than the Type B gutter inlet on the milder cross-slope. On the steeper cross-slope, their performance characteristics are similar.

4. HYDRAULIC PERFORMANCE OF INLETS IN SAG LOCATIONS

4.1 General Principles

The depth-discharge relationship for an inlet in a sag location can be computed from fundamental hydraulic principles of orifice flow and weir flow. The application of these principles to inlets in sag locations is explained in the FHWA's Hydraulic Engineering Circular No. 12, *Drainage of Highway Pavements* (FHWA, 1984). The discharge into the inlet can be limited by weir flow (critical flow) around the perimeter of the opening or depressed area or by orifice flow (full flow) through the inlet opening.

The starting point for the analysis of weir flow into an inlet is the formula for the unit discharge (discharge per unit width normal to the direction of flow), q, in a critical-flow section,

$$q = 0.385 \sqrt{2\,g}\; d^{3/2} \qquad (8)$$

in which d is the specific energy (depth plus velocity head) at the critical-flow section. The specific energy at the critical-flow section is the ponded depth, referenced to the bottom level at the critical-flow section. Water enters the inlet from the front (the street side) and from the gutters on each side. On the street side, the critical-flow section is horizontal, so the frontal discharge, Q_f, is given by the formula

$$Q_f = 0.385\, L \sqrt{2g}\, d^{3/2} \qquad (9)$$

in which L is the length of the critical-flow section. On the gutter sides, the bottom has a significant cross-slope, so d varies across the critical-flow section. For a bottom with a constant cross-slope, the formula for the side discharge, Q_s, is

$$Q_s = 0.385\, L \sqrt{2g}\, \frac{1}{m} \left(d_1^{5/2} - d_2^{5/2} \right) \qquad (10)$$

where m is the cross-slope of the critical-flow section, d_1 is specific energy at the lowest point in the cross-section and d_2 is specific energy at the highest point in the cross-section. This formula is obtained by integration of Eq. 8 over the cross-section. For a critical-flow section with two different cross-slopes (e.g., the cross-slope of the gutter and the cross-slope of the curb face), m_1 and m_2, the weir-flow formula is

$$Q_s = 0.385\, L \sqrt{2g}\, \frac{2}{5} \left[\frac{1}{m_1} \left(d_1^{5/2} - d_2^{5/2} \right) + \frac{1}{m_2} \left(d_2^{5/2} - d_3^{5/2} \right) \right] \qquad (11)$$

in which d_1 is the specific energy at the outer edge of segment 1, d_2 is the specific energy at the intersection of segments 1 and 2, and , and d_3 is specific energy at the outer edge of segment 2.

TABLE 1. Design Curves for Inlet Performance on Grade

Inlet type	S_x (%)	S_o (%)	Eq. #	Qo m^3/s	Qa (m^3/s)	k
Concrete gutter inlet	1.6	0.5 – 5.0	7	0.01	--	1.29
	3.1	0.5 – 5.0	6	0	0.12	--
Type B gutter inlet	1.6	0.5 – 5.0	7	0	--	1.385
	3.1	0.5 – 5.0	7	0	--	1.57
Type 12 combination inlet	1.6	0.5 – 5.0	7	0.01	--	1.41
	3.1	0.5 – 5.0	7	0.02	--	1.43
Type 22 curb inlet, 1.5 m	1.6	0.5	6	0.01	0.114	--
		1.0	6	0.01	0.087	--
		2.0	6	0.01	0.068	--
		3.0	6	0.01	0.060	--
		5.0	6	0.01	0.050	--
	3.1	0.5	6	0.01	0.122	--
		1.0	6	0.01	0.092	--
		2.0	6	0.01	0.068	--
		3.0	6	0.01	0.060	--
		5.0	6	0.01	0.045	
Type 22 curb inlet, 3.0 m	1.6	0.5 – 5.0	6	0	0.195	--
	3.1	0.5	6	0.02	0.270	--
		1.0	6	0.02	0.240	--
		2.0	6	0.02	0.195	--
		3.0	6	0.02	0.175	--
		5.0	6	0.02	0.155	--
Type 22 curb inlet, 4.5 m	1.6	0.5 – 5.0	7	0.03	--	1.64
	3.1	0.5 – 5.0	7	0.06	--	1.70

In applying the weir-flow formulas, the key issue is the location of the critical-flow section. The location of critical-flow section depends on the geometry of the area around the inlet opening. Critical flow does not necessarily occur at the perimeter of the inlet opening. In some cases, the exact location of critical flow is uncertain and must be estimated. The location of critical flow can vary with the depth of ponding.

The general formula for the discharge into an inlet under orifice-flow conditions is

$$Q = C_c \, A_o \sqrt{2 g h_o} \tag{12}$$

in which C_c is the contraction coefficient, A_o is area of the opening, and h_o is the depth of the ponded water measured from the centroid of the opening.

4.2 Concrete Gutter Inlet

The front edge of the concrete gutter inlet structure is depressed 13 mm below the edge of the pavement. The critical-flow section for the frontal flow would most likely be located at the edge of the pavement rather than the edge of the inlet opening. In computing the frontal discharge, critical flow is assumed to occur at the edge of the pavement. This assumption is conservative. If critical flow actually occurred at the edge of the inlet opening, the specific energy would be higher and the discharge would be larger. The length of the weir crest for the frontal flow would be approximately 1.00 m, the total length of the inlet structure. The flow from the sides would pass through critical approximately where the gutter section terminates at the inlet structure. The standard gutter is 850 mm wide with the outer edge 40 mm above the edge of the pavement. The flowline of the gutter is 600 mm from the edge of the pavement and approximately 40 mm below the edge of the pavement. The formula for the total discharge into the concrete gutter inlet by weir flow is

$$Q = 1.705\left\{1.00\left(\frac{d}{1000}\right)^{3/2} + 2\cdot\frac{2}{5}\left[\frac{600}{40}\left(\left(\frac{d+40}{1000}\right)^{5/2} - \left(\frac{d}{1000}\right)^{5/2}\right) + \frac{250}{40}\left(\frac{d+40}{1000}\right)^{5/2}\right]\right\} \tag{13}$$

in which d is the depth of the ponded water in mm, measured from the edge of the pavement, and Q is in m^3/s. Table 2 shows computed discharges for ponded depths up to 40 mm (the top of the gutter). The discharge into the concrete gutter inlet is controlled by the weir-flow condition over the entire range of possible depths.

4.3 Type B Gutter Inlet

The Type B gutter inlet is depressed slightly below the gutter of the Type I combined curb and gutter. The front edge of the Type B inlet structure slopes steeply (17% slope) toward the grated opening. The critical-flow section for the frontal flow would most likely be located at the edge of the pavement rather than the edge of the inlet opening. The length of the weir crest for the frontal flow would be approximately 0.91 m, the total length of the inlet structure. The flow from the sides is assumed to pass through critical at the side edges of the inlet structure. Based on these assumptions and the dimensions and geometry of the inlet structure, the formula for the total discharge into the Type B gutter inlet by weir flow is

$$Q = 1.705\left\{0.91\left(\frac{d}{1000}\right)^{3/2} + 2\cdot\frac{2}{5}\left[\frac{450}{35}\left(\left(\frac{d+60}{1000}\right)^{5/2} - \left(\frac{d+25}{1000}\right)^{5/2}\right) + \frac{150}{25}\left(\left(\frac{d+25}{1000}\right)^{5/2} - \left(\frac{d}{1000}\right)^{5/2}\right)\right]\right\} \tag{14}$$

in which d is the depth of the ponded water in mm, measured from the edge of the pavement, and Q is in m^3/s. Table 2 shows computed discharges for ponded depths up to 105 mm (the top of the curb). The discharge into the Type B gutter inlet is controlled by the weir-flow condition over the entire range of possible depths.

TABLE 2. Discharges Captured by Inlets in Sag Locations

Depth at edge of pavement (mm)	Captured discharge (m^3/s)					
	Concrete gutter inlet	Type B	Type 12	Type 22, 1.5 m	Type 22, 3.0 m	Type 22, 4.5 m
0	0.008	0.015	0.035	0.035	0.035	0.035
5	0.011	0.018	0.039	0.040	0.041	0.042
10	0.015	0.022	0.044	0.046	0.048	0.051
15	0.020	0.027	0.049	0.052	0.057	0.061
20	0.025	0.032	0.055	0.059	0.066	0.073
25	0.031	0.037	0.061	0.066	0.076	0.087
30	0.038	0.043	0.067	0.074	0.087	0.101
35	0.045	0.049	0.074	0.082	0.099	0.116
40	0.052	0.055	0.081	0.091	0.111	0.132
45		0.062	0.089	0.100	0.124	0.149
50		0.069	0.096	0.109	0.138	0.166
55		0.076	0.104	0.119	0.152	0.185
60		0.083	0.112	0.129	0.167	0.204
65		0.091	0.120	0.139	0.182	0.224
70		0.099	0.129	0.150	0.197	.0245
75		0.107	0.138	0.161	0.213	0.266
80		0.116	0.147	0.172	0.23	0.288
85		0.124	0.156	0.184	0.247	0.310
90		0.133	0.165	0.188	0.264	0.334
95		0.142	0.175	0.191	0.282	0.357
100		0.151	0.185	0.193	0.301	0.382
105		0.161	0.195	0.196	0.319	0.406

4.4 Type 12 Combination Inlet

The Type 12 combination inlet is depressed below the gutter of the Type I combined curb and gutter. The transition from the normal gutter to the inlet structure is 760 mm long. The flowline of the gutter falls 80 mm within the transition. The front edge of the Type 12 inlet structure slopes steeply (20% slope) toward the grated opening. The critical-flow section for the frontal flow would most likely be located at the edge of the pavement rather than the edge of the inlet opening. The length of the weir crest for the frontal flow would be at least 0.91 m, the total length of the inlet structure. The flow from the sides is assumed to pass through critical at the side edges of the inlet opening. The flow from the sides might actually pass through critical at the start of the transition from the normal gutter. This would result in less flow from the sides, but it would increase the effective length of the weir crest for frontal flow, and result in a larger overall discharge. Therefore, the assumption of critical flow at the side edges of the inlet opening is conservative. Based on these assumptions and the dimensions and geometry of the inlet structure, the formula for the total discharge into the Type 12 combination inlet by weir flow is

$$Q = 1.705\left\{0.91\left(\frac{d}{1000}\right)^{3/2} + 2\cdot\frac{2}{5}\cdot\frac{610}{120}\left[\left(\frac{d+120}{1000}\right)^{5/2} - \left(\frac{d}{1000}\right)^{5/2}\right]\right\} \tag{15}$$

in which d is the depth of the ponded water in mm, measured from the edge of the pavement, and Q is in m^3/s. Table 2 shows computed discharges for ponded depths up to 105 mm (the top of the curb). The discharge into the Type 12 combination inlet is controlled by the weir-flow condition over the entire range of possible depths.

4.5 Type 22 Curb Inlet

The Type 22 curb inlets are depressed below the gutter of the Type I combined curb and gutter. The transition from the normal gutter to the inlet structure is 760 mm long. The flowline of the gutter falls 80 mm within the transition. The concrete surface in front of the Type 22 inlet slopes steeply (19% slope) toward the grated opening. The critical-flow section for the frontal flow would most likely be located at the edge of the pavement rather than the edge of the inlet opening. The length of the weir crest for the frontal flow would equal or exceed total length of the inlet structure (1.5, 3.0 or

4.5 m). The flow from the sides is assumed to pass through critical at the side edges of the inlet opening (a conservative assumption). Based on these assumptions and the dimensions and geometry of the inlet structure, the formula for the total discharge into a Type 22 curb inlet by weir flow is

$$Q = 1.705 \left\{ L \left(\frac{d}{1000} \right)^{3/2} + 2 \cdot \frac{2}{5} \cdot \frac{625}{120} \left[\left(\frac{d + 120}{1000} \right)^{5/2} - \left(\frac{d}{1000} \right)^{5/2} \right] \right\} \qquad (16)$$

in which L is the total length of the inlet structure in meters, d is the depth of the ponded water in mm, measured from the edge of the pavement, and Q is in m^3/s.

The Type 22 inlet must also be analyzed for orifice-flow control. The effective cross-sectional area of the inlet opening in m^2 is 0.101 (L-0.300), where L is the total length of the inlet structure. This quantity is the area of the opening at the brink of the overfall into the inlet box, measured perpendicular to the sloping top of the opening. The centroid of this area is 91 mm below the edge of the pavement. Directly upstream of the brink, the planes of the top and bottom concrete surfaces converge at an angle of 24.4°. This situation is similar to flow under a partially raised radial gate. The contraction coefficient, C_c, for a radial gate varies with the angle of convergence, , according to the formula C_c = 1 - 0.75 + 0.36 ^{2} (Henderson, 1966). The contraction coefficient for = 24.4° is 0.823. The lateral contraction of the inflow would be negligible because the sides of the entrance are well rounded (125-mm radius of curvature). Based on these assumptions and the dimensions and geometry of the inlet structure, the formula for the discharge into a Type 22 curb inlet by orifice flow is

$$Q = 0.823\,(0.101)\,(L - 0.300)\,\sqrt{19.62\,(d + 0.091)} \qquad (17)$$

in which L is the total length of the inlet structure in meters, d is the depth of the ponded water in mm, measured from the edge of the pavement, and Q is in m^3/s.

Table 2 shows computed discharges for ponded depths up to 105 mm (the top of the curb). The discharge into the 1.5-m Type 22 inlet is controlled by the orifice-flow condition for depths of ponding over 80 mm, and by the weir-flow condition for shallower depths. The discharges into the

3.0-m and 4.5-m Type 22 inlets are controlled by the weir-flow condition over the entire range of possible depths.

5. SPREAD OF WATER ON ROADWAYS

The spread of water on a roadway depends on many factors. The principal factors are the discharge, the dimensions of the curb and gutter, the grade and cross-slope of the roadway, and the roughness of the gutter and pavement. Although the discharge increases in the direction of flow, the principles of uniform flow govern the local depth-discharge relationship. The Manning equation cannot be applied directly to the entire cross-section of the flow due to the extreme variation in depth across the section. However, the depth-averaged velocity at any location within the cross-section can be obtained from the Manning equation with the hydraulic radius replaced by the local depth. Integration of the product of this local velocity and the local depth leads to the Izzard formula for discharge. Manning friction factors (n values) for gutters and streets typically range from 0.013 to 0.016, depending on condition (Chow, 1959; FHWA, 1996).

The spread on a street with a standard gutter or a Type I combination curb and gutter can be estimated with the design charts in Appendix C. These charts were developed by Izzard's method using a Manning n value of 0.016. Because they are based on a rougher-than-average condition, these charts should provide reasonably conservative estimates of spread.

6. CONCLUSIONS

The performance characteristics of KDOT's standard curb and gutter inlets have been determined from hydraulic model tests and theoretical calculations. Model tests of inlets on grade provided the relationships between captured discharge and total discharge for grades from 0.5% to 5.0% and cross-slopes of 1.6% and 3.1%. The three inlets with gutter openings (the concrete gutter inlet, Type B gutter inlet and Type 12 combination inlets) perform similarly under all conditions tested. The grade of the roadway does not have a significant effect on performance of these inlets. The Type 22 curb inlets perform better on mild grades than on steep grades. All of the inlets perform slightly better on the steeper cross-slope. The design charts in Appendix B are based on the minimum performance characteristics from the model tests.

The depth-discharge relationships for the inlets in sag locations, shown in Table 2, were computed from fundamental hydraulic principals of orifice flow and weir flow. The concrete gutter inlet has a much smaller capacity than the other inlets in sag locations due to the low profile of the standard gutter. The spread of water on a street with a standard gutter or a Type I combination curb and gutter can be estimated with the design charts in Appendix C.

The design aids in this report provide a sound basis for the selection and sizing of curb and gutter inlets. More accurate sizing of inlets could improve roadway safety and reduce drainage costs.

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Appendix A

Graphs of Experimental Results for Inlets on Grade

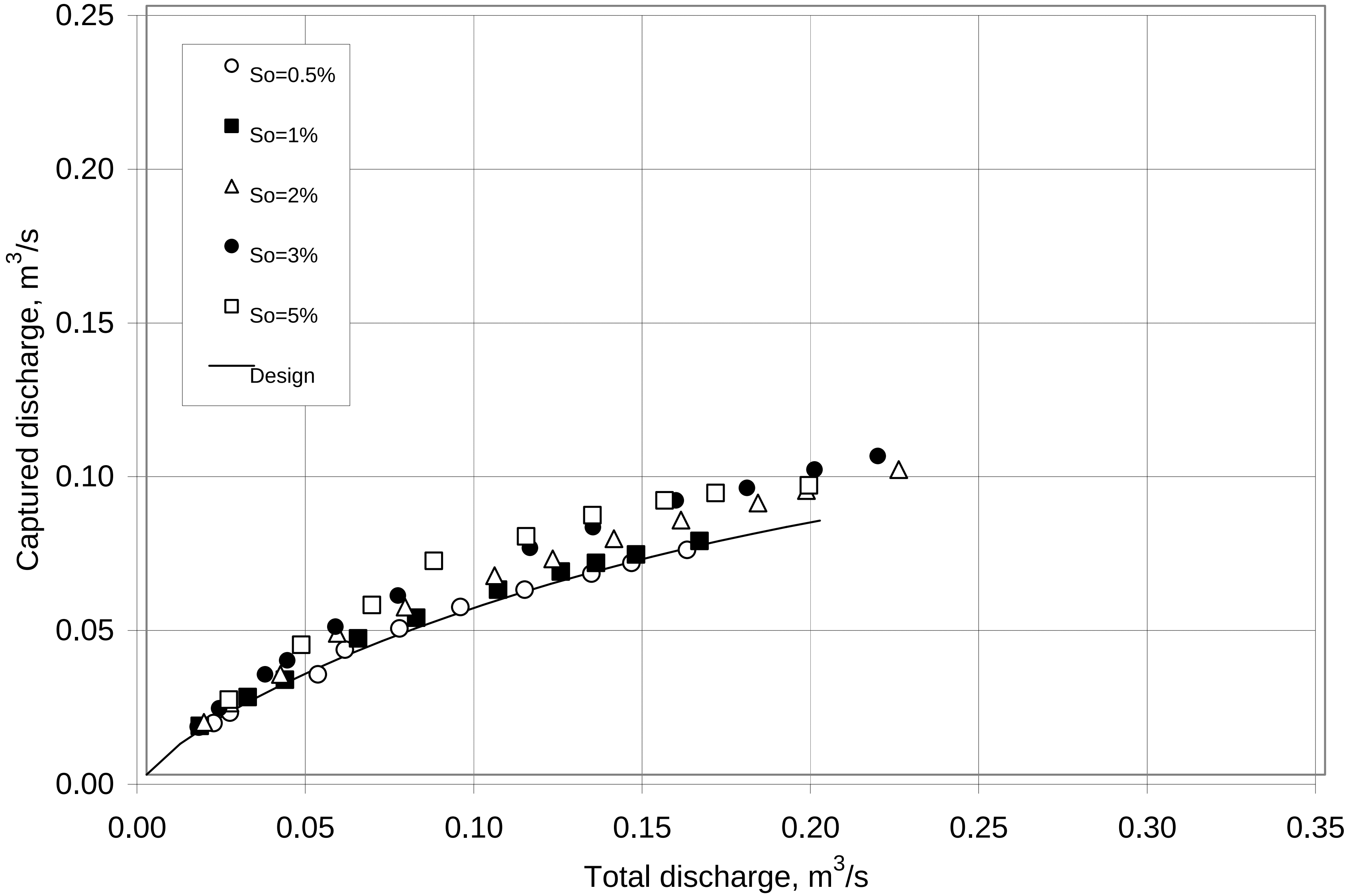

Fig. A.1. Concrete Gutter Inlet on Pavement with 1.6% Cross-Slope

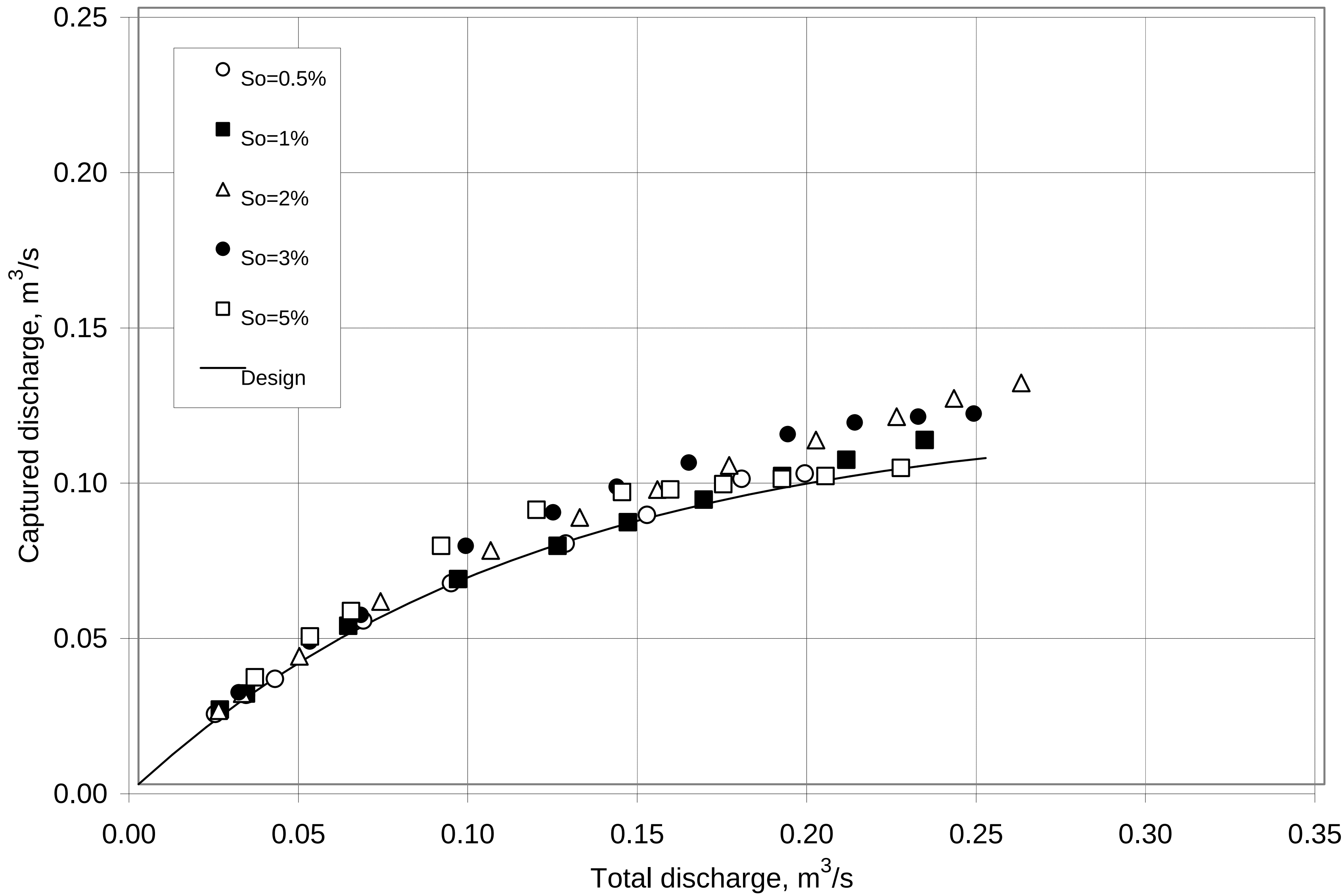

Fig. A.2. Concrete Gutter Inlet on Pavement with 3.1% Cross-Slope

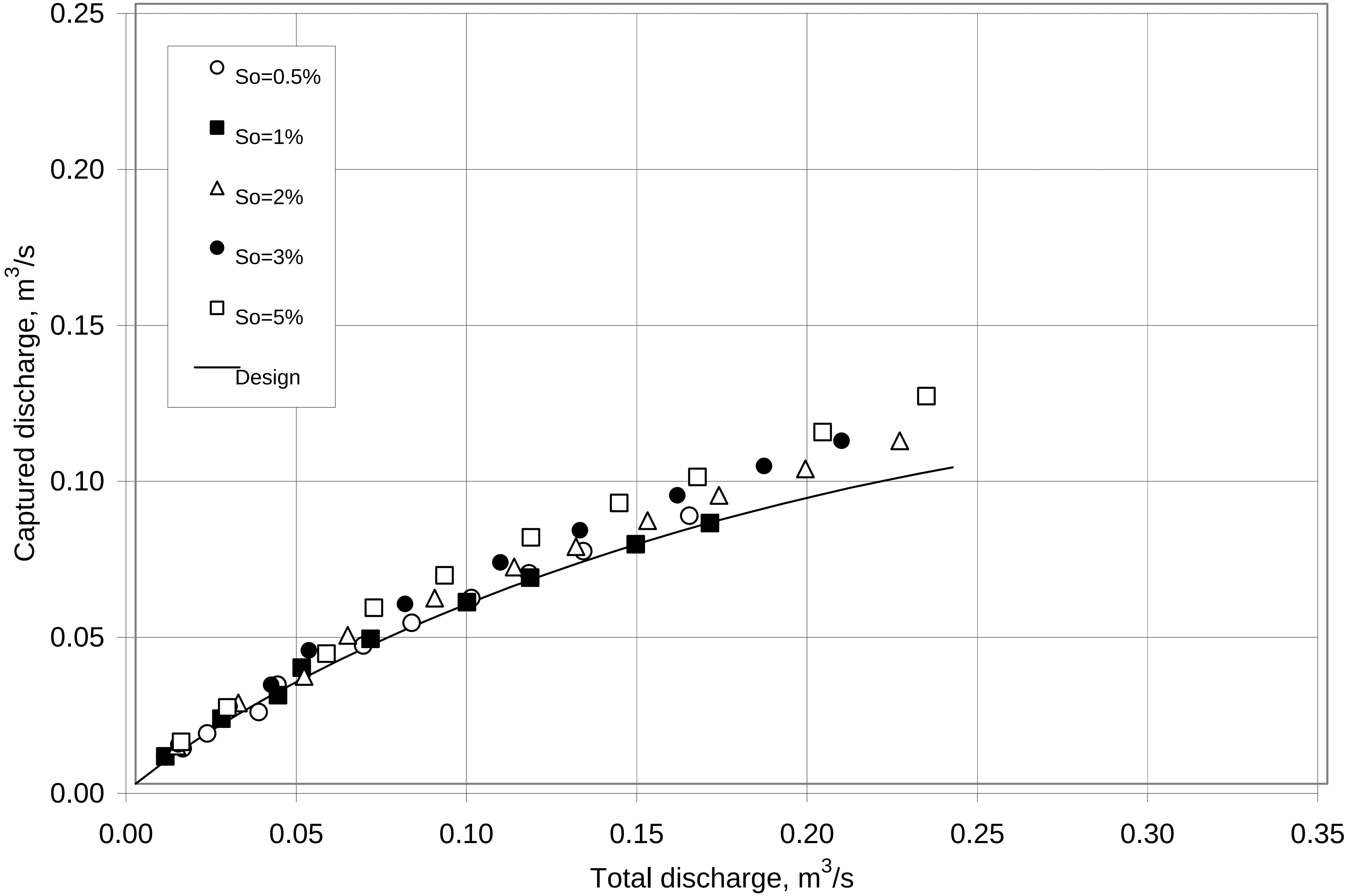

Fig. A.3. Type B Gutter Inlet on Pavement with 1.6% Cross-Slope

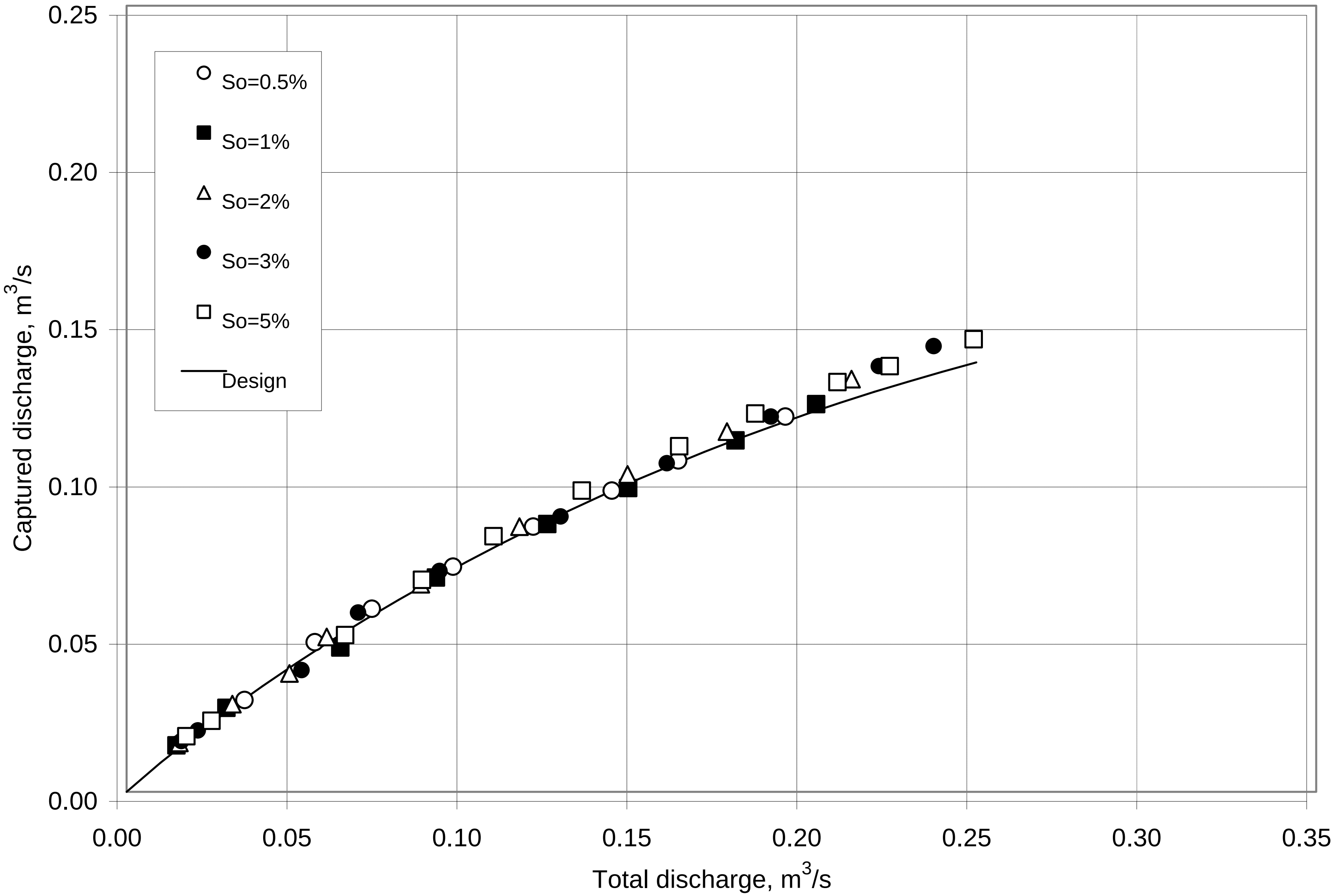

Fig. A.4. Type B Gutter Inlet on Pavement with 3.1% Cross-Slope

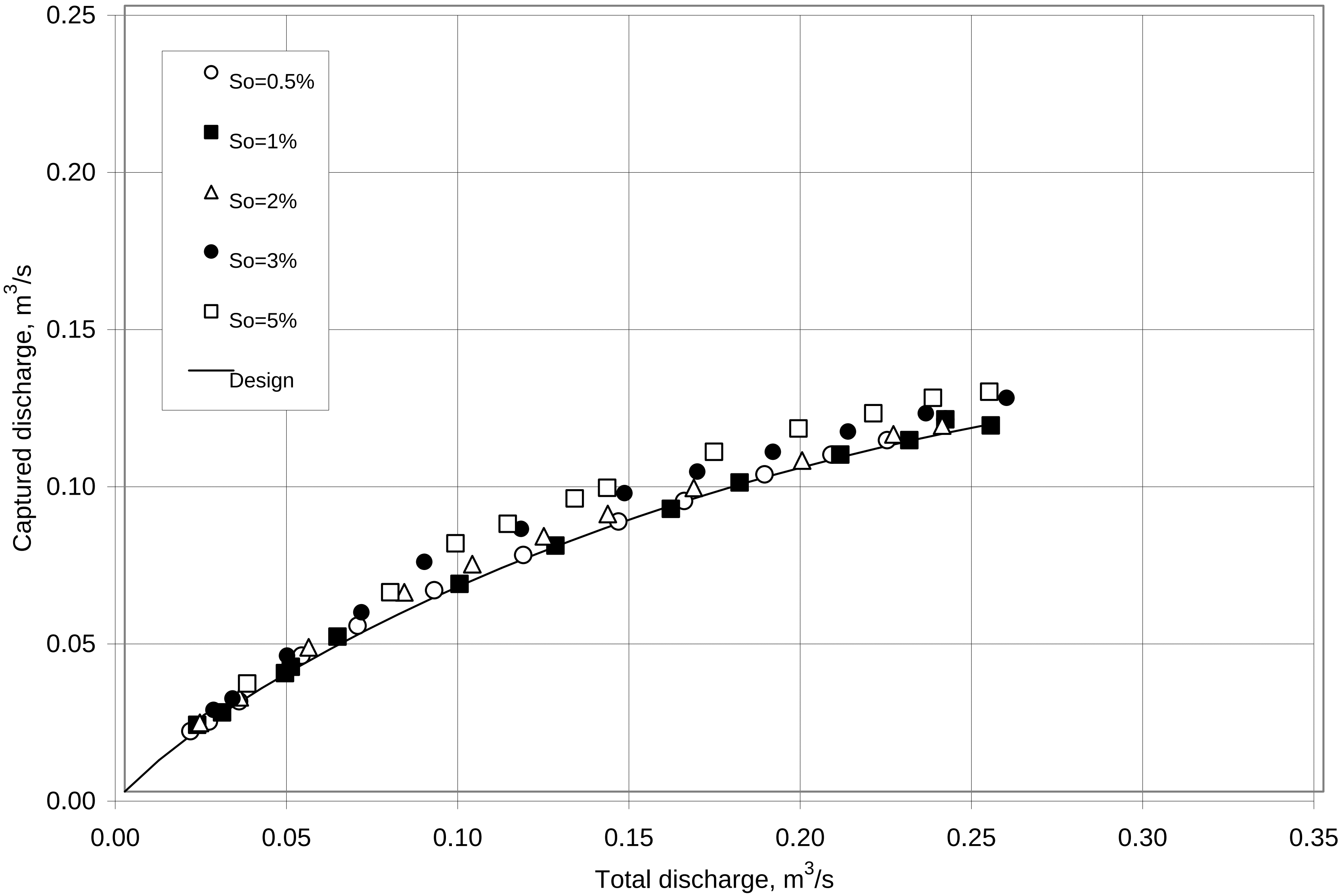

Fig. A.5. Type 12 Combination Inlet on Pavement with 1.6% Cross-Slope

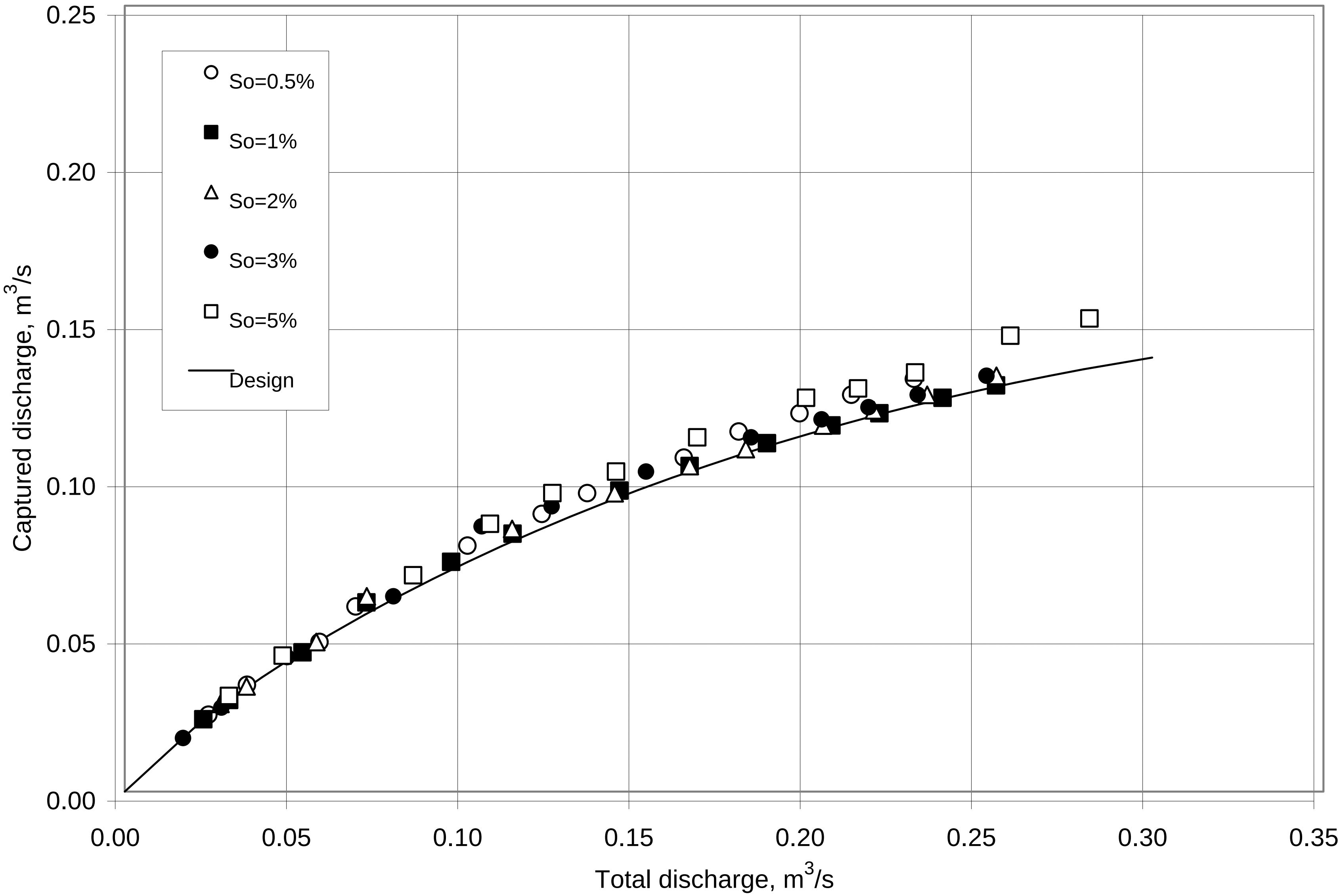

Fig. A.6. Type 12 Combination Inlet on Pavement with 3.1% Cross-Slope

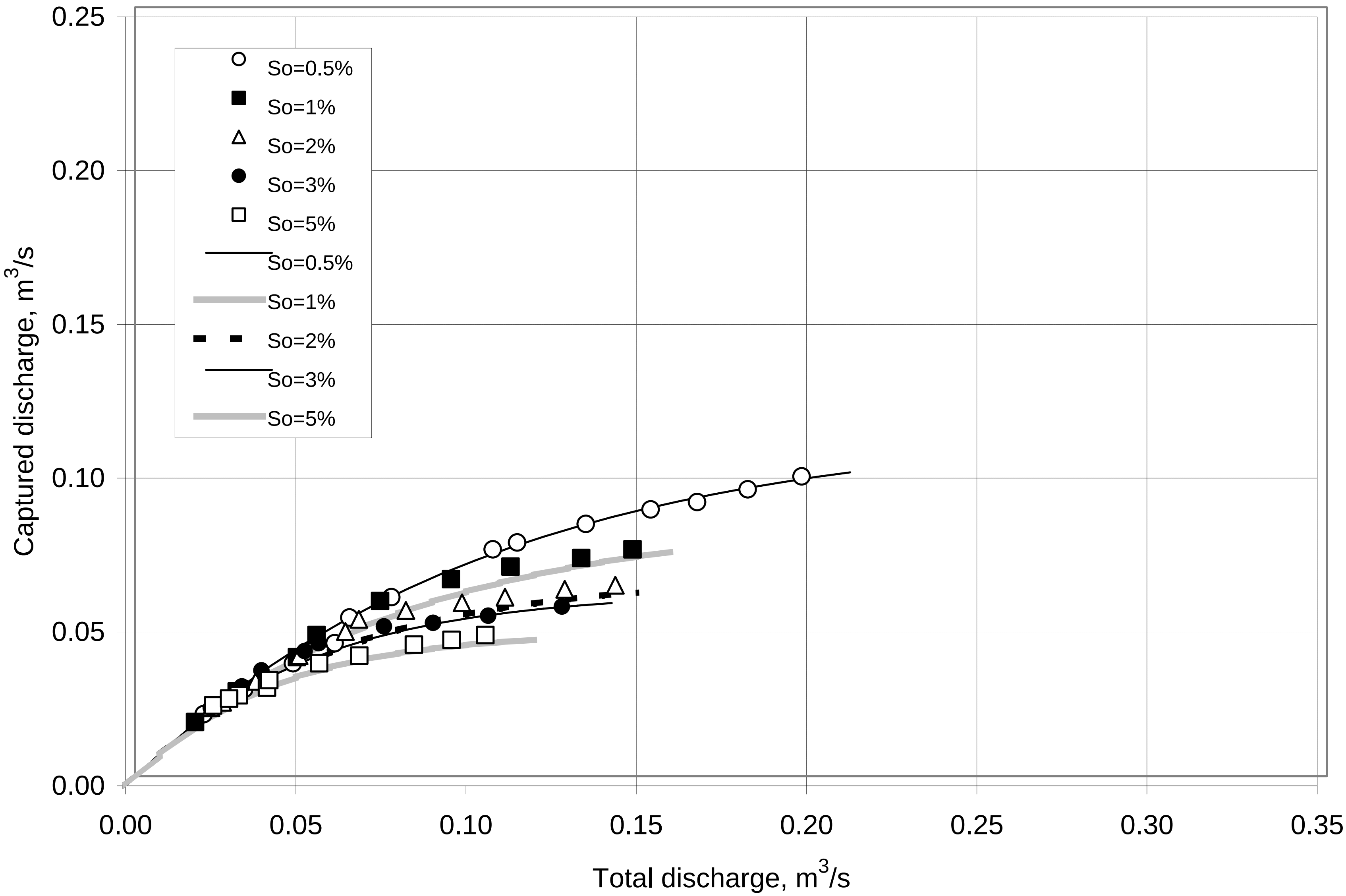

Fig. A.7. Type 22 Curb Inlet, 1.5 m, on Pavement with 1.6% Cross-Slope

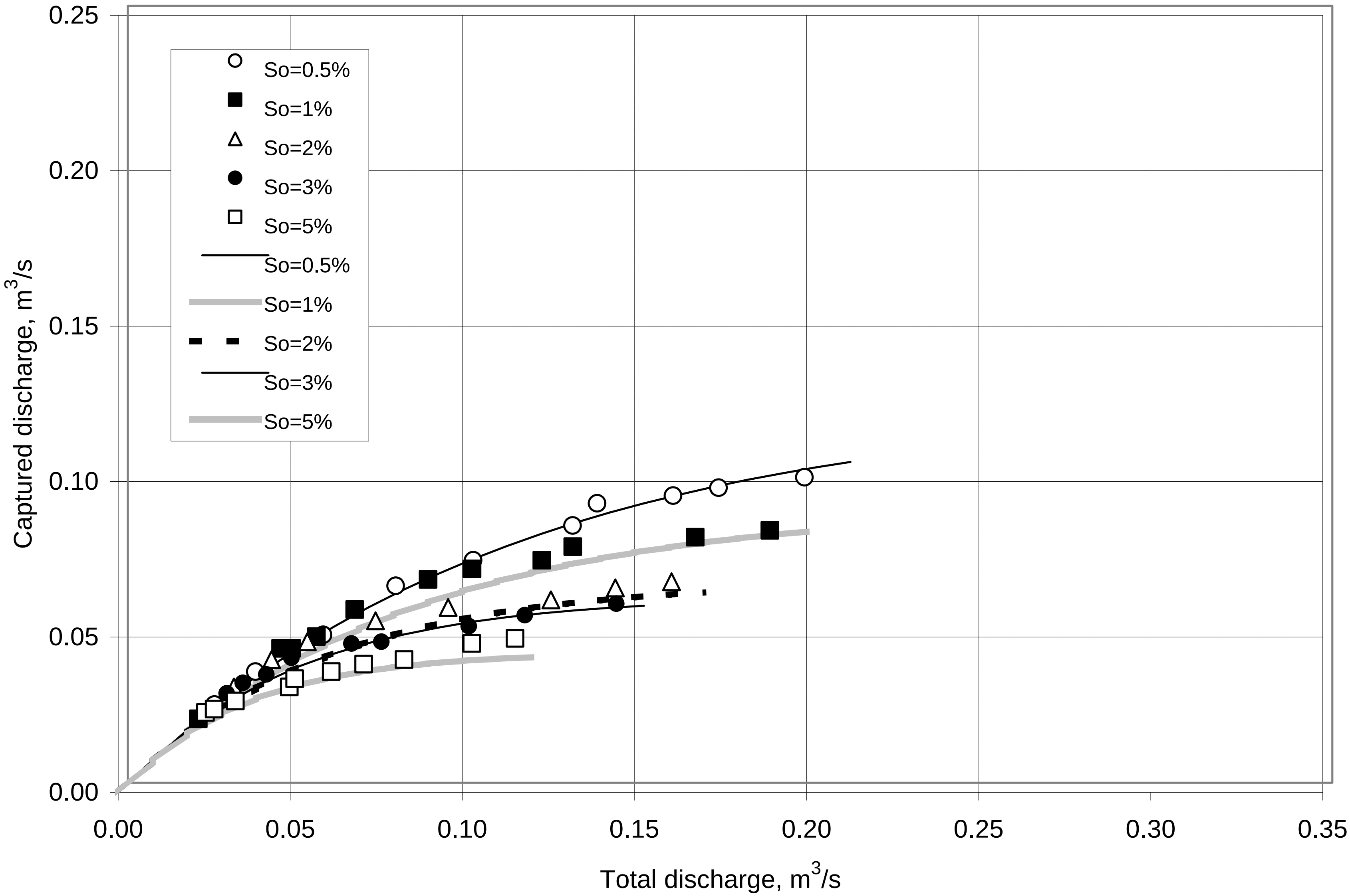

Fig. A.8. Type 22 Curb Inlet, 1.5 m, on Pavement with 3.1% Cross-Slope

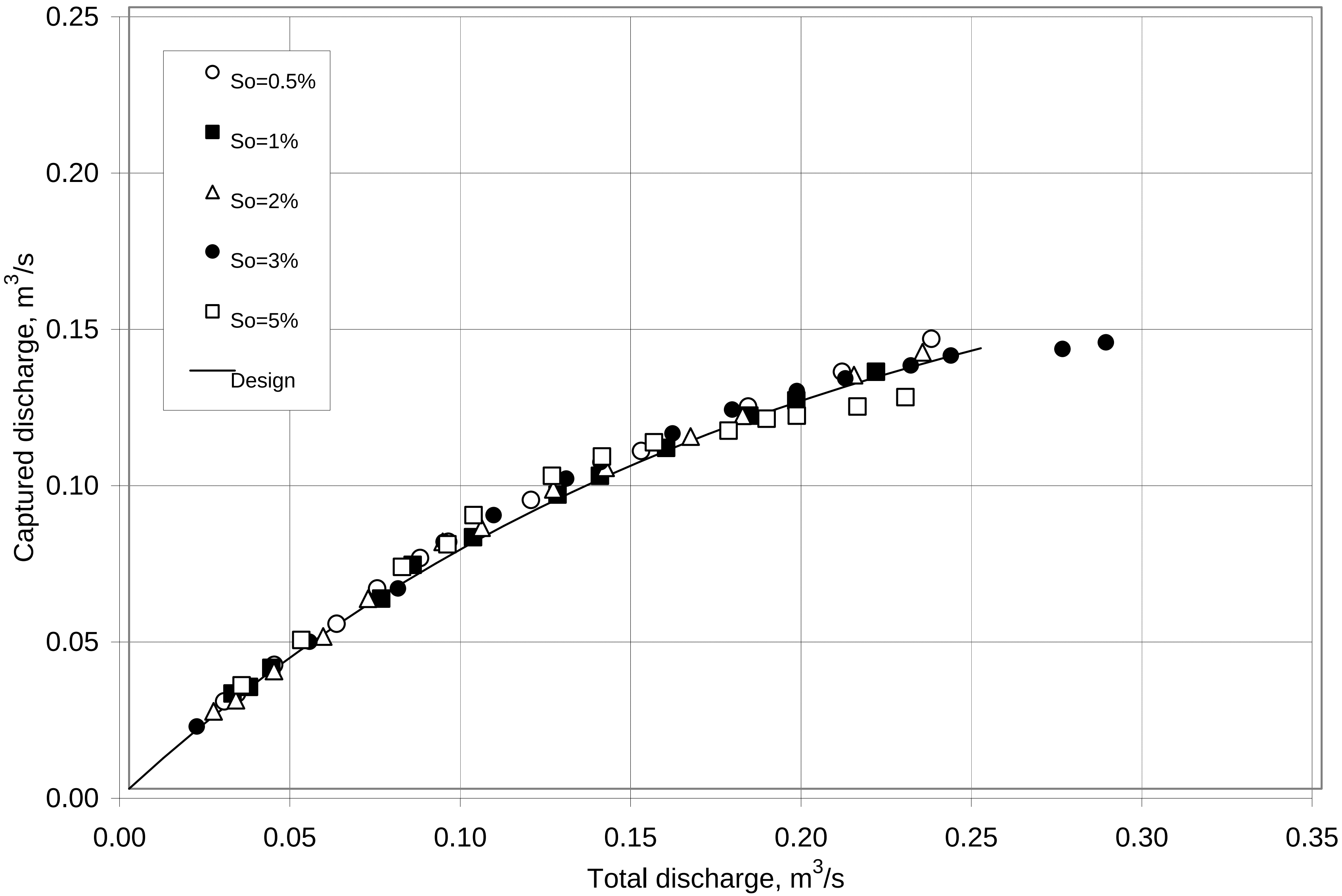

Fig. A.9. Type 22 Curb Inlet, 3.0 m, on Pavement with 1.6% Cross-Slope

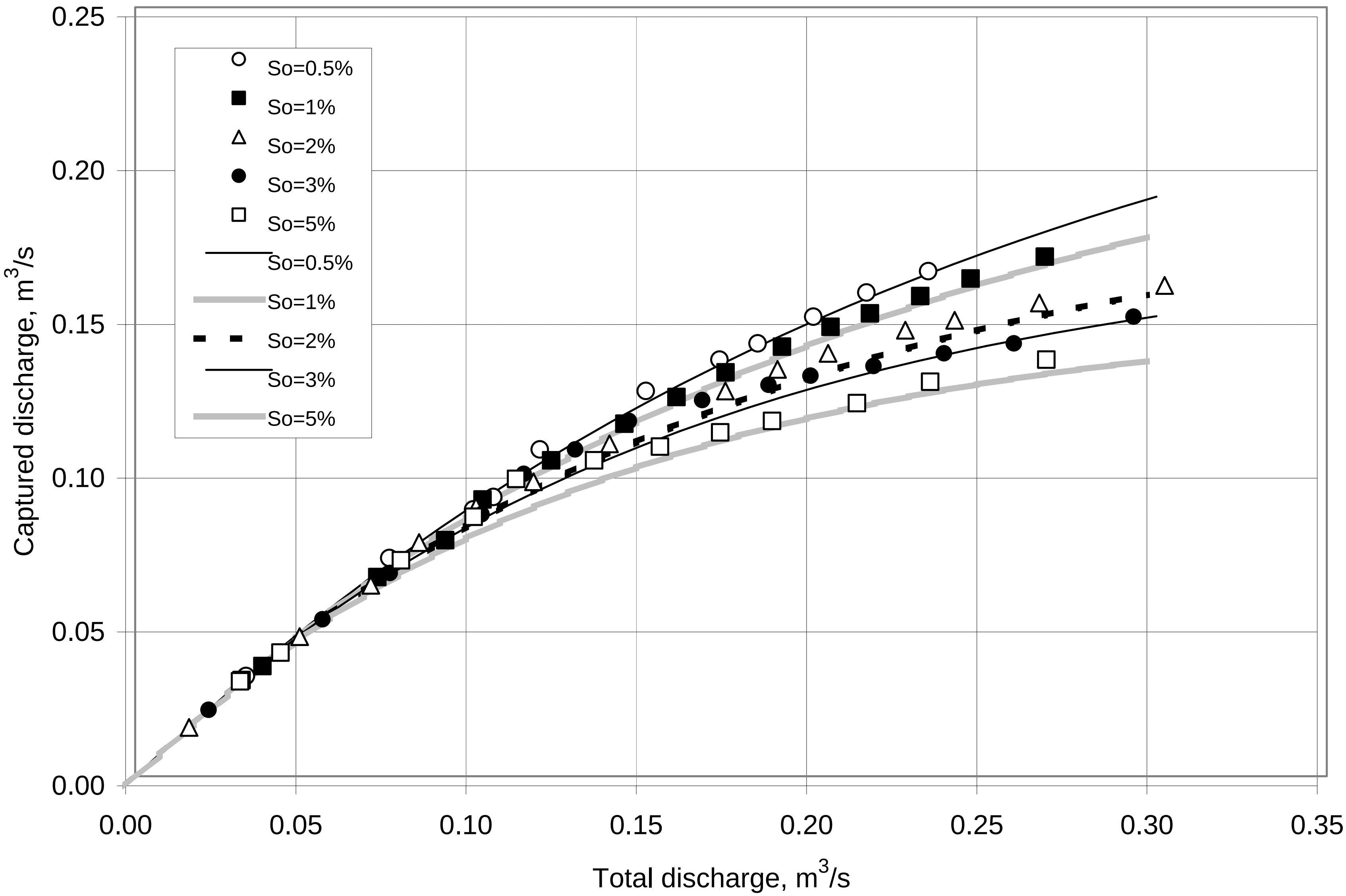

Fig. A.10. Type 22 Curb Inlet, 3.0 m, on Pavement with 3.1% Cross-Slope

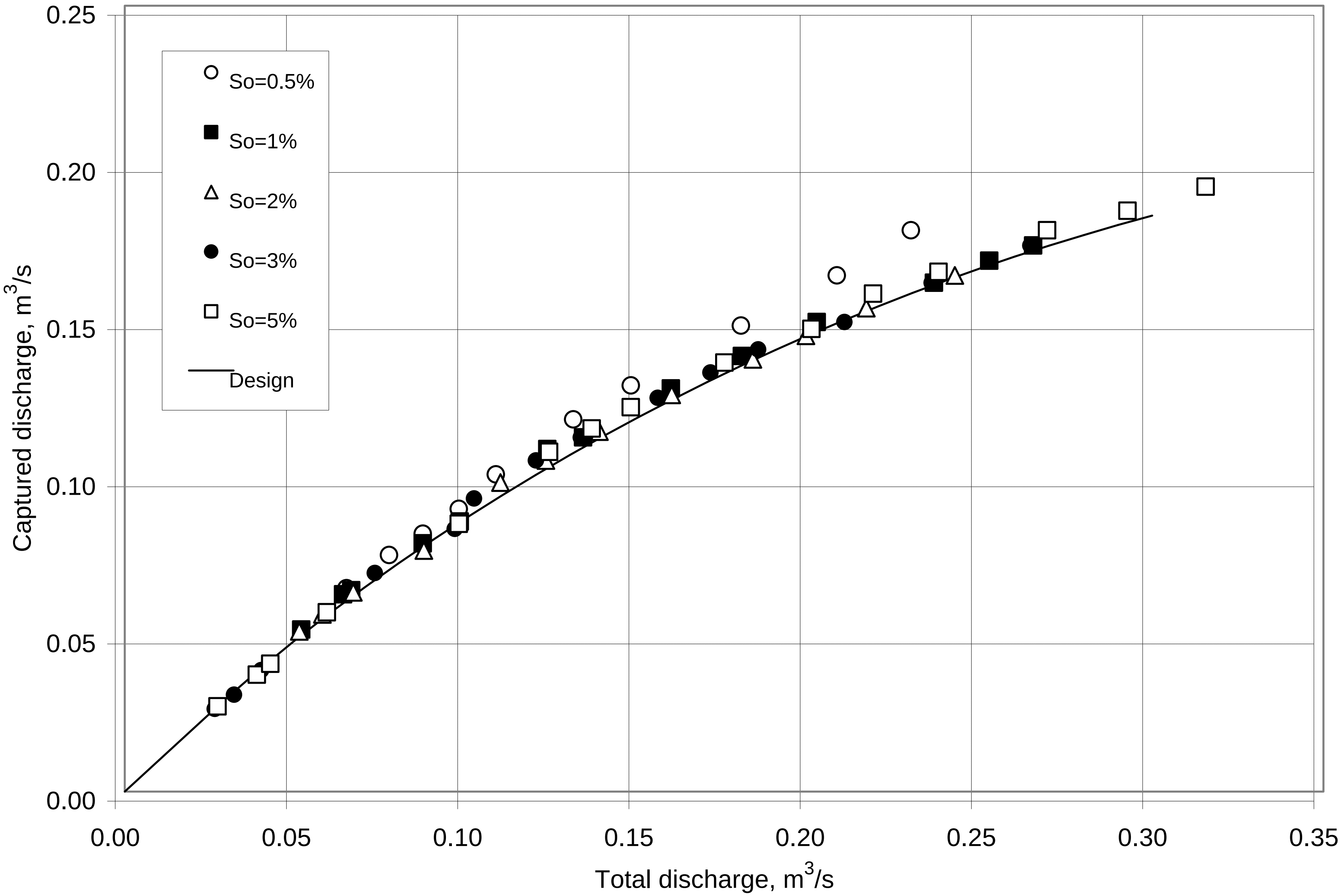

Fig. A.11. Type 22 Curb Inlet, 4.5 m, on Pavement with 1.6% Cross-Slope

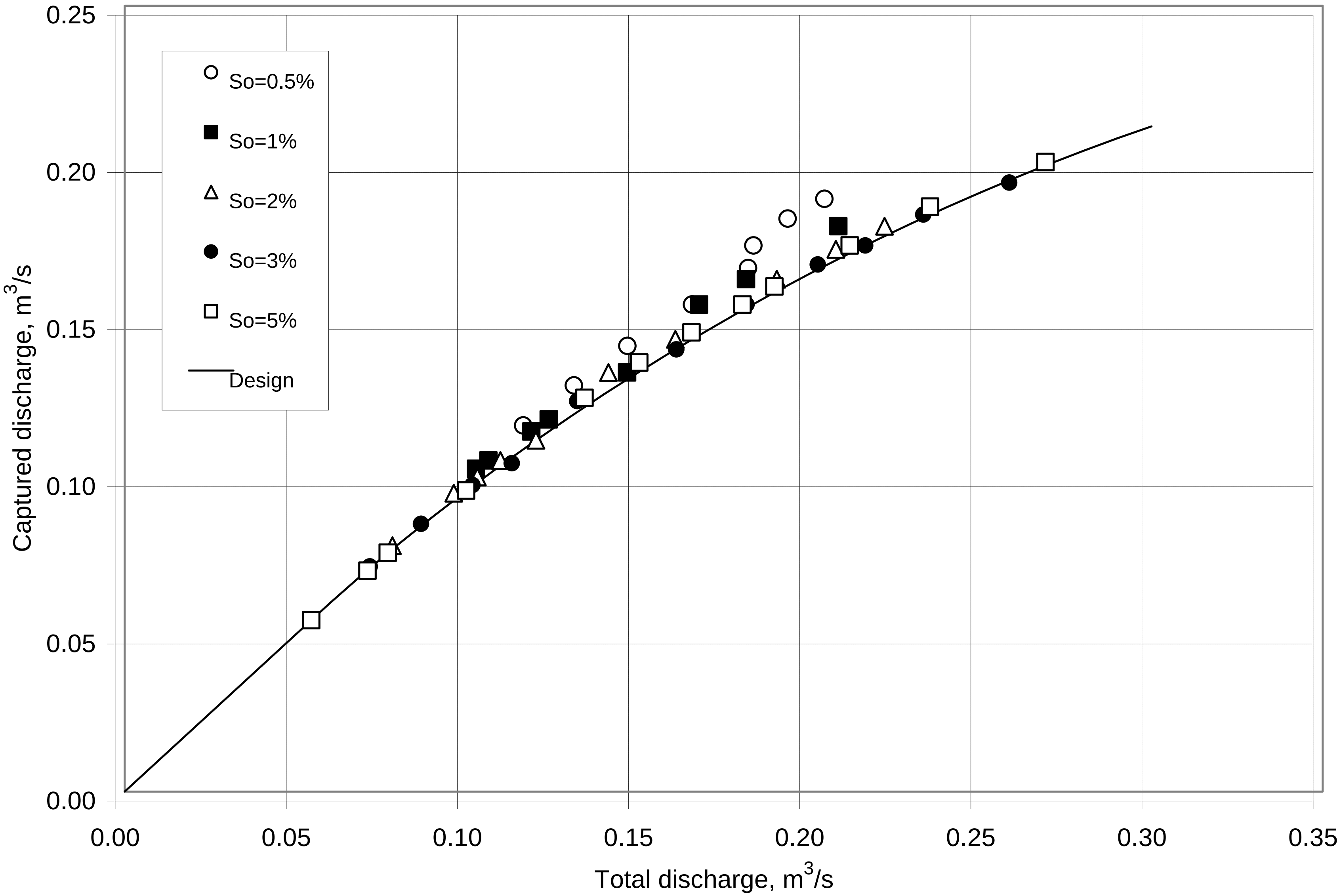

Fig. A.12. Type 22 Curb Inlet, 4.5 m, on Pavement with 3.1% Cross-Slope

Appendix B

Design Charts for Inlets on Grade

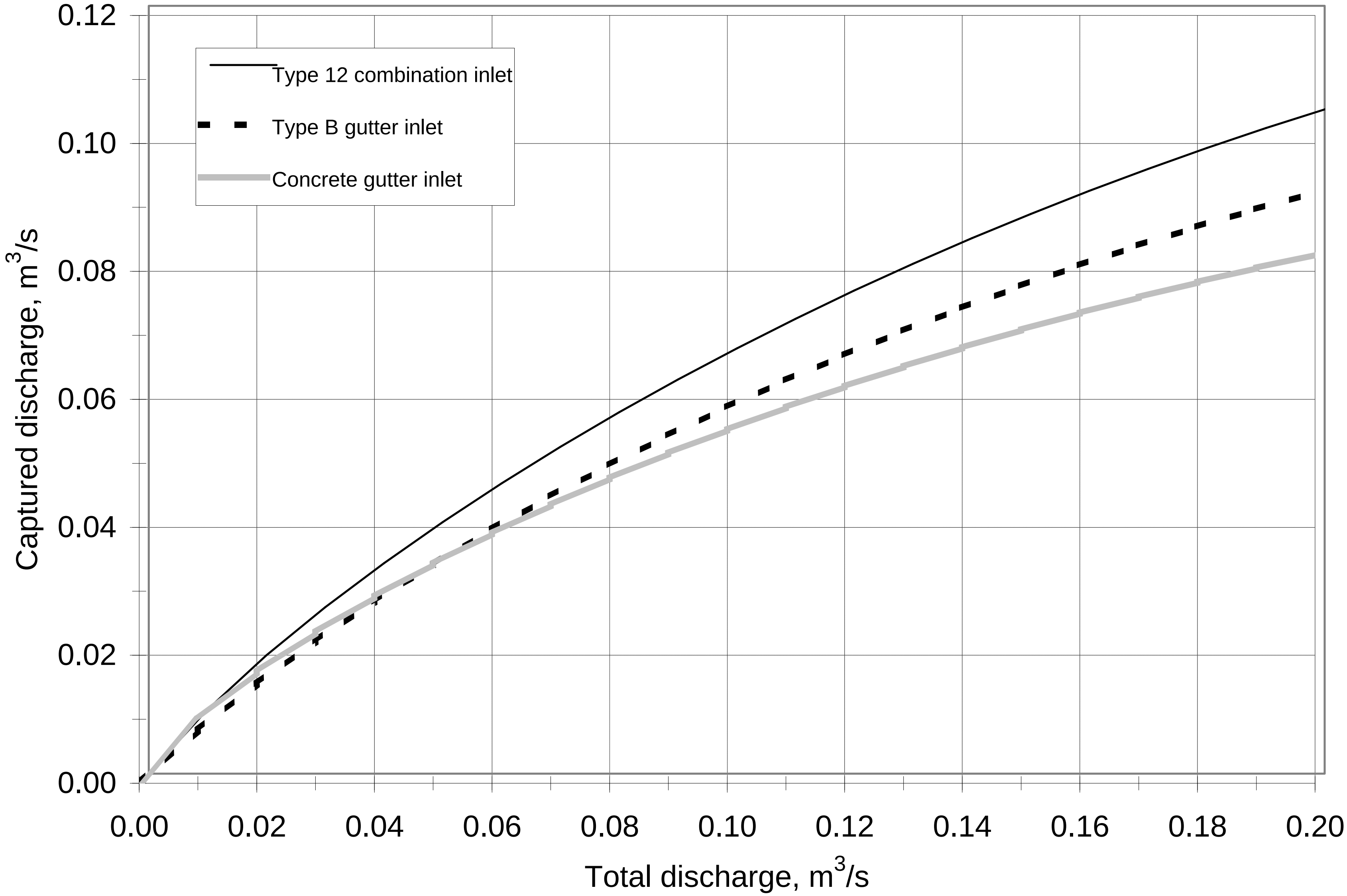

Fig. B.1. Gutter and Combination Inlets on Pavements with 1.6% Cross-Slopes

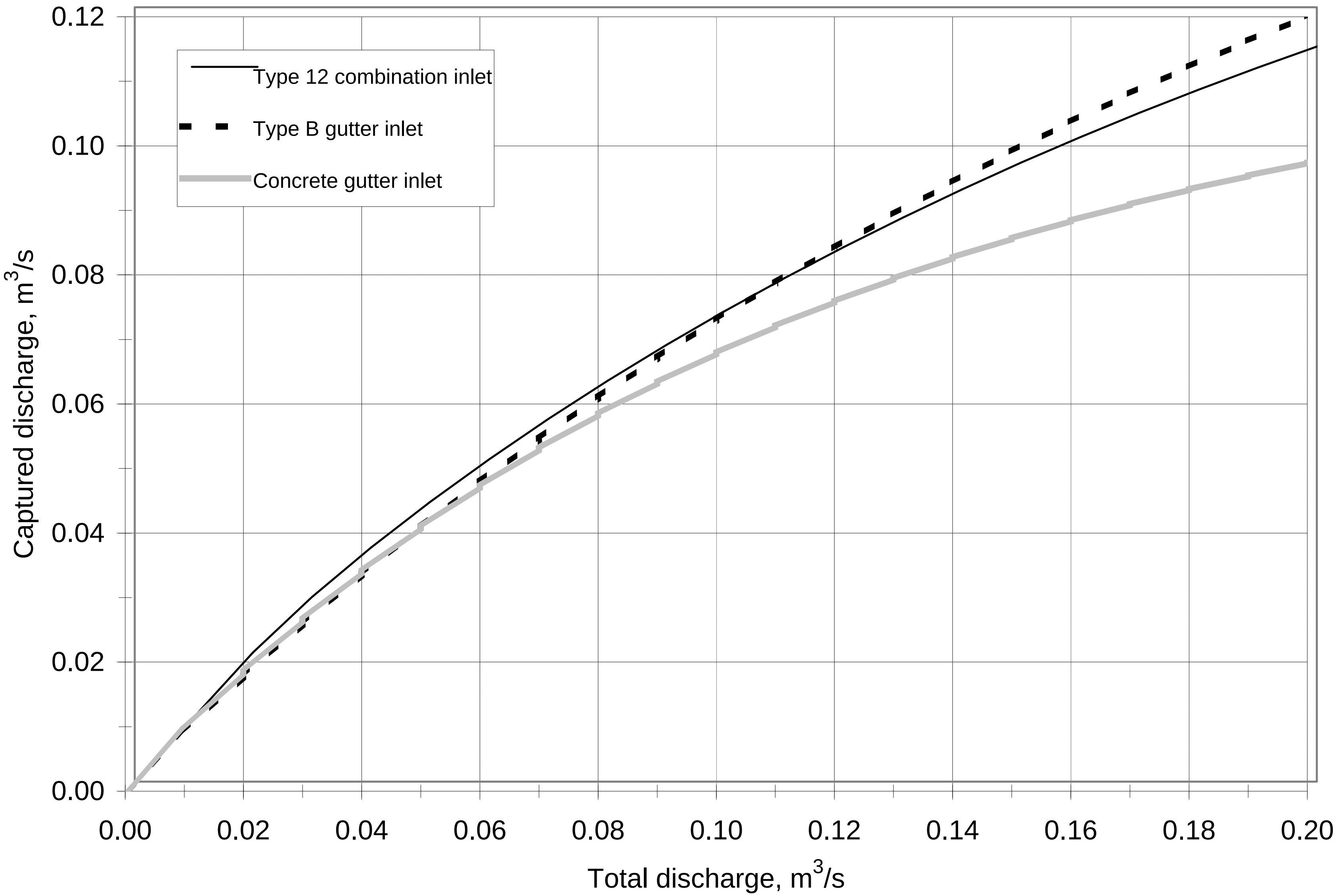

Fig. B.2. Gutter and Combination Inlets on Pavement with 3.1% Cross-Slope

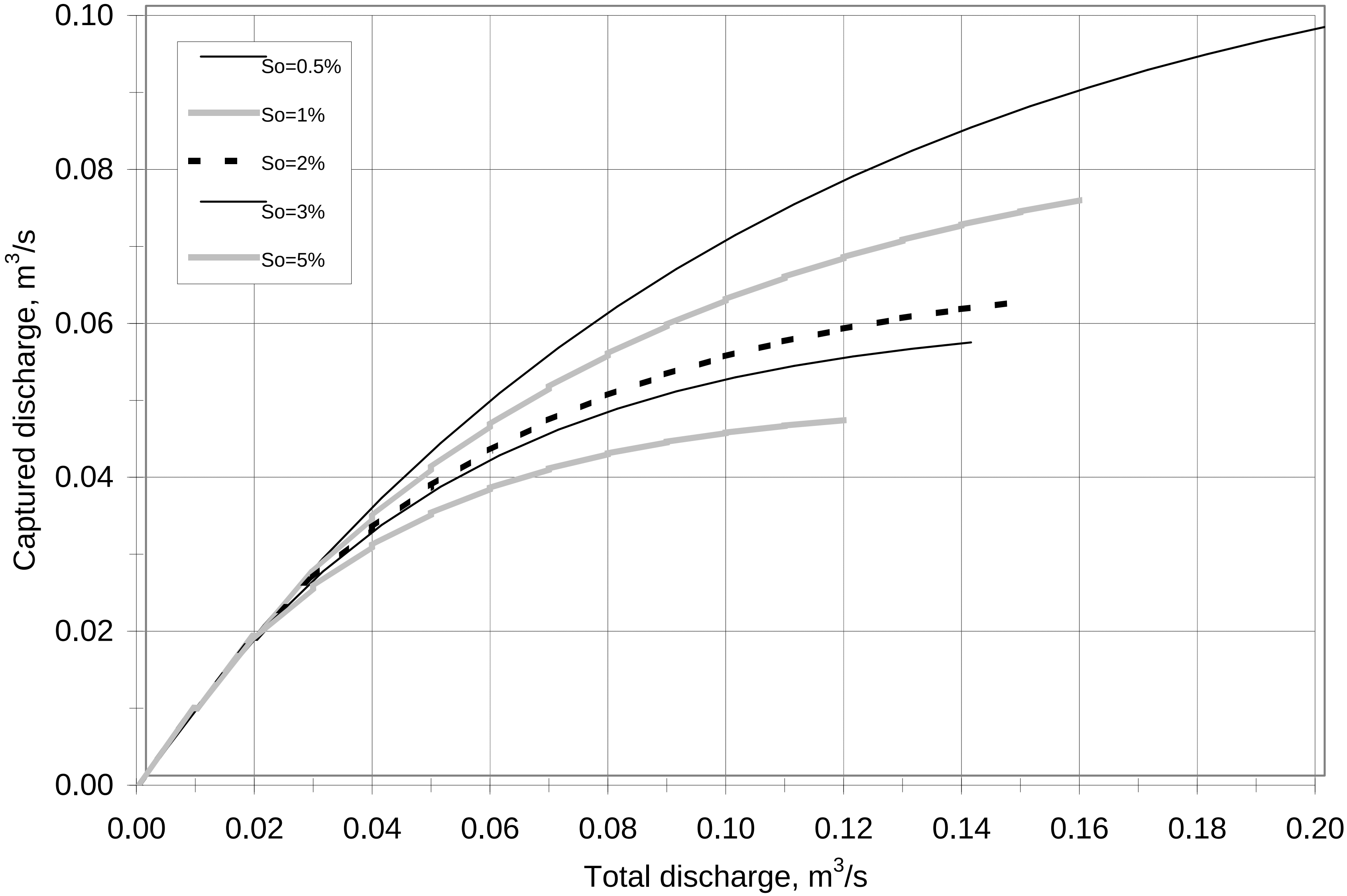

Fig. B.3. Type 22 Curb Inlet, 1.5 m, on Pavement with 1.6% Cross-Slope

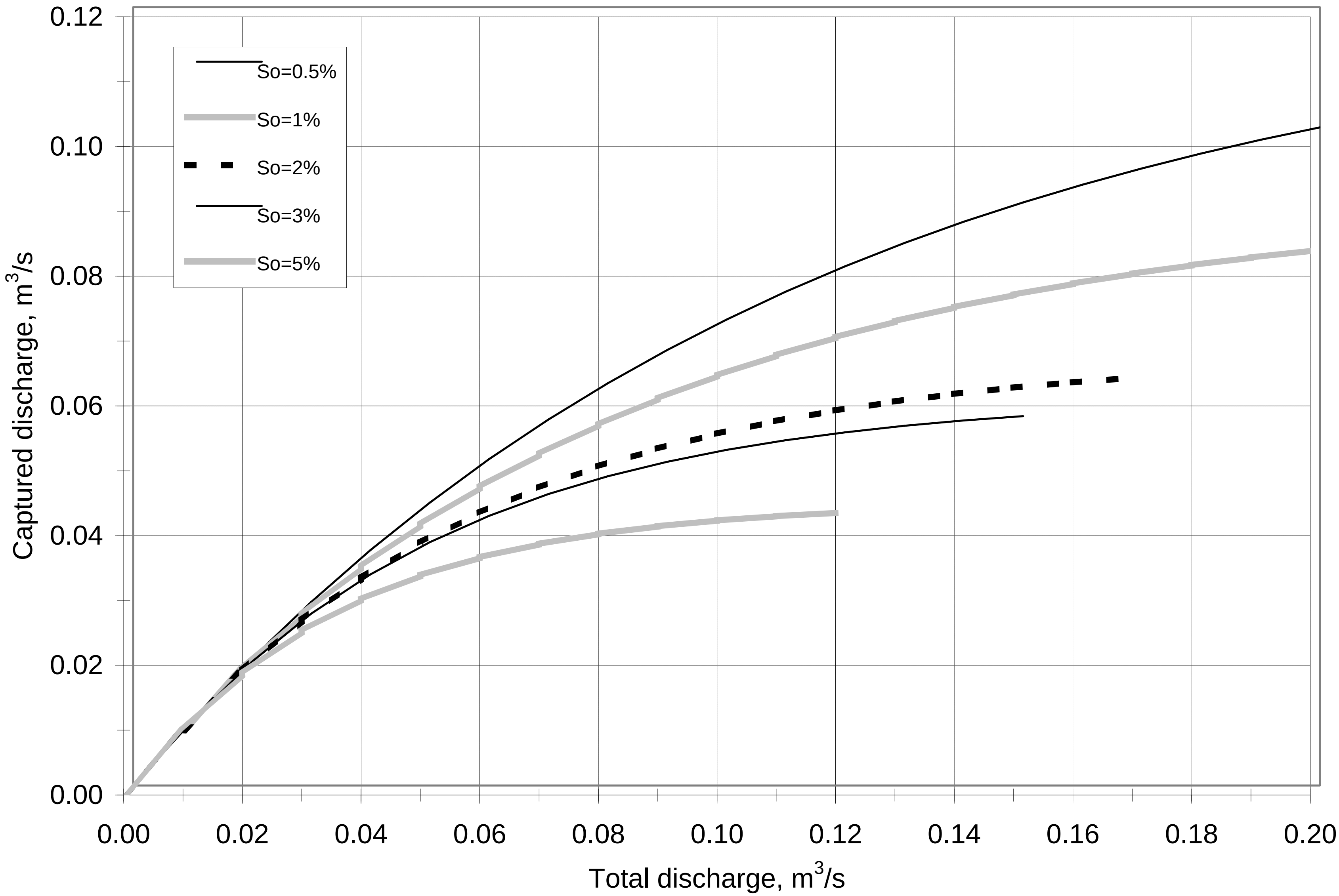

Fig. B.4. Type 22 Curb Inlet, 1.5 m, on Pavement with 3.1% Cross-Slope

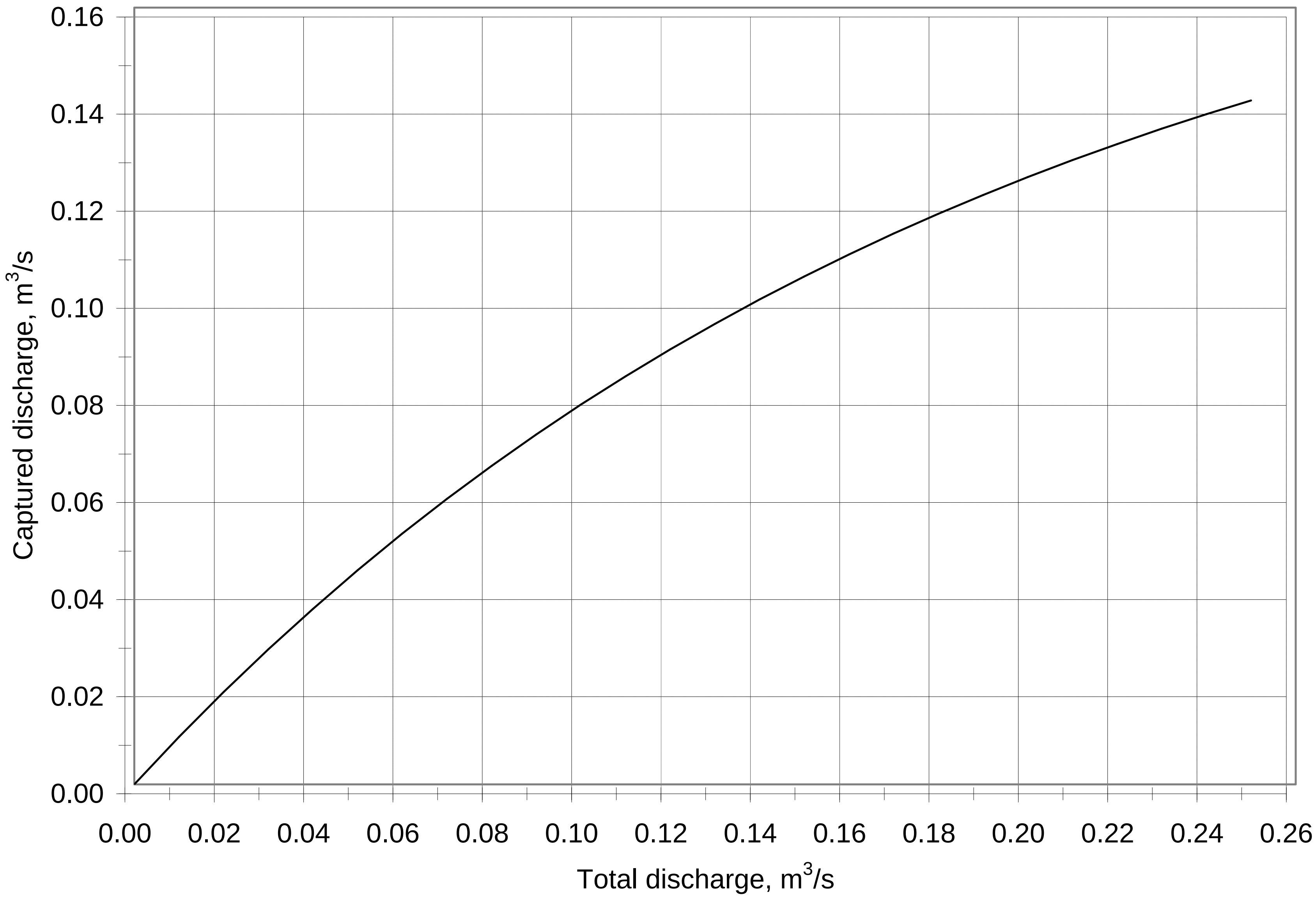

Fig. B.5. Type 22 Curb Inlet, 3.0 m, on Pavement with 1.6% Cross-Slope

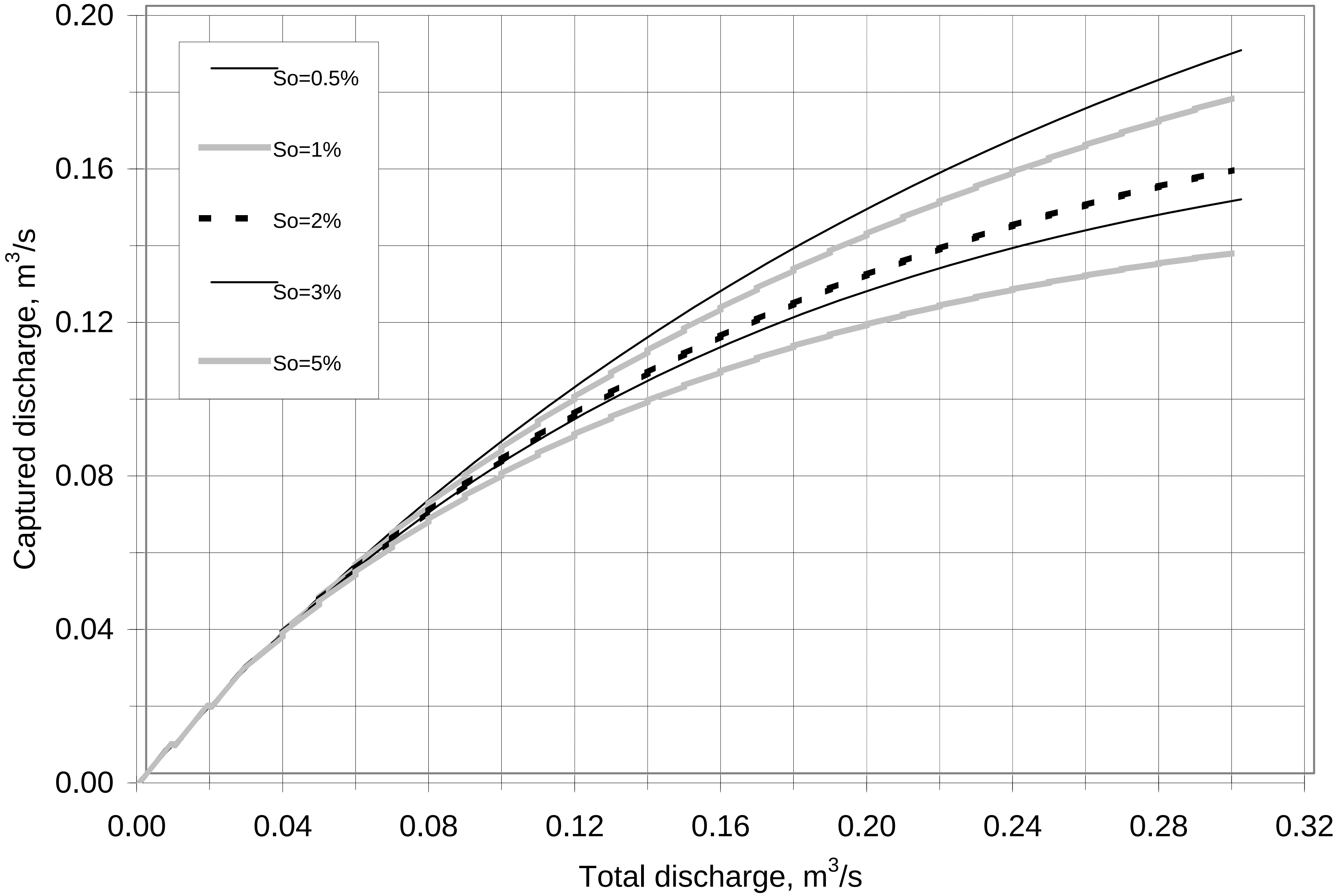

Fig. B.6. Type 22 Curb Inlet, 3.0 m, on Pavement with 3.1% Cross-Slope

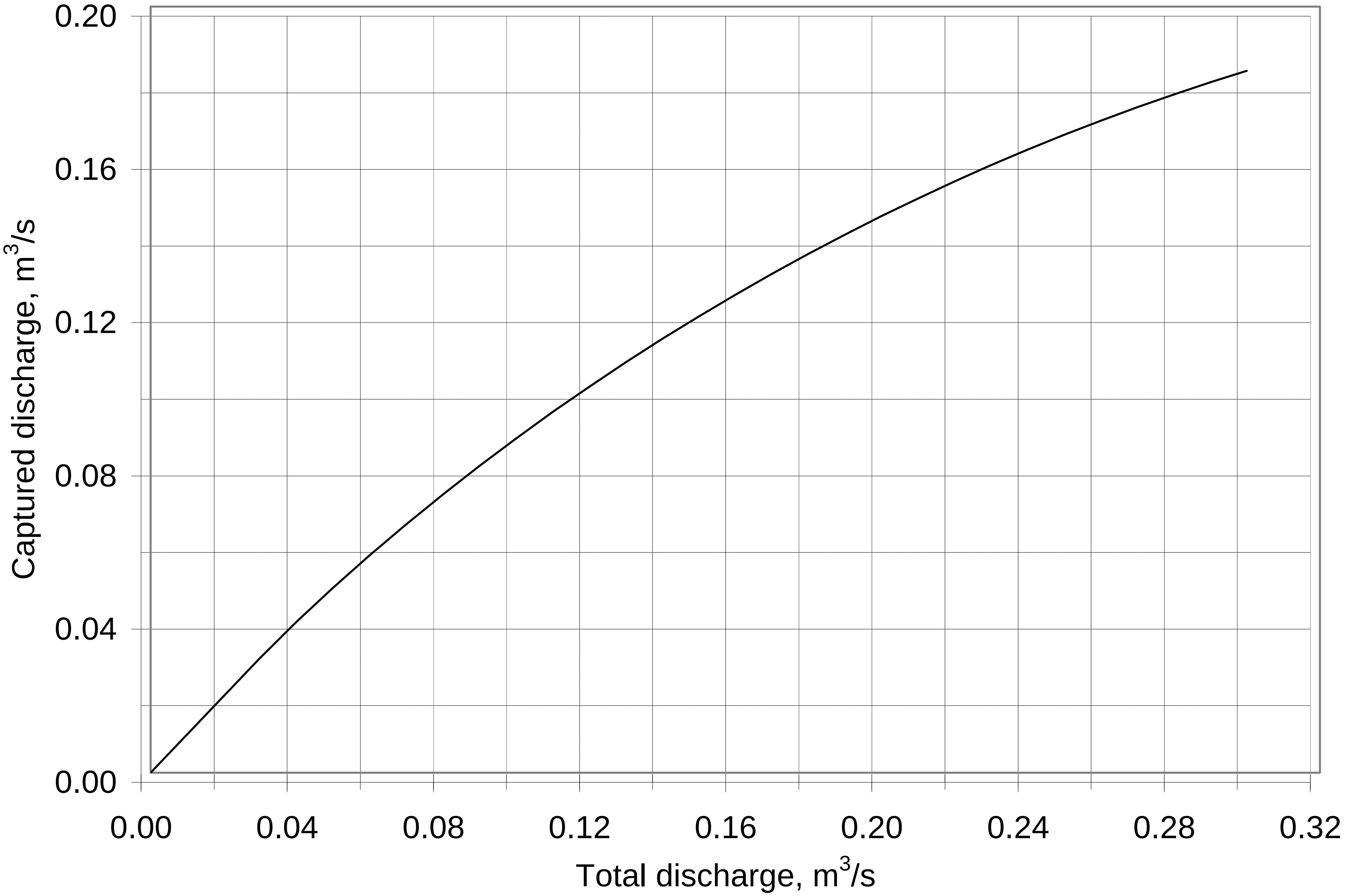

Fig. B.7. Type 22 Curb Inlet, 4.5 m, on Pavement with 1.6% Cross-Slope

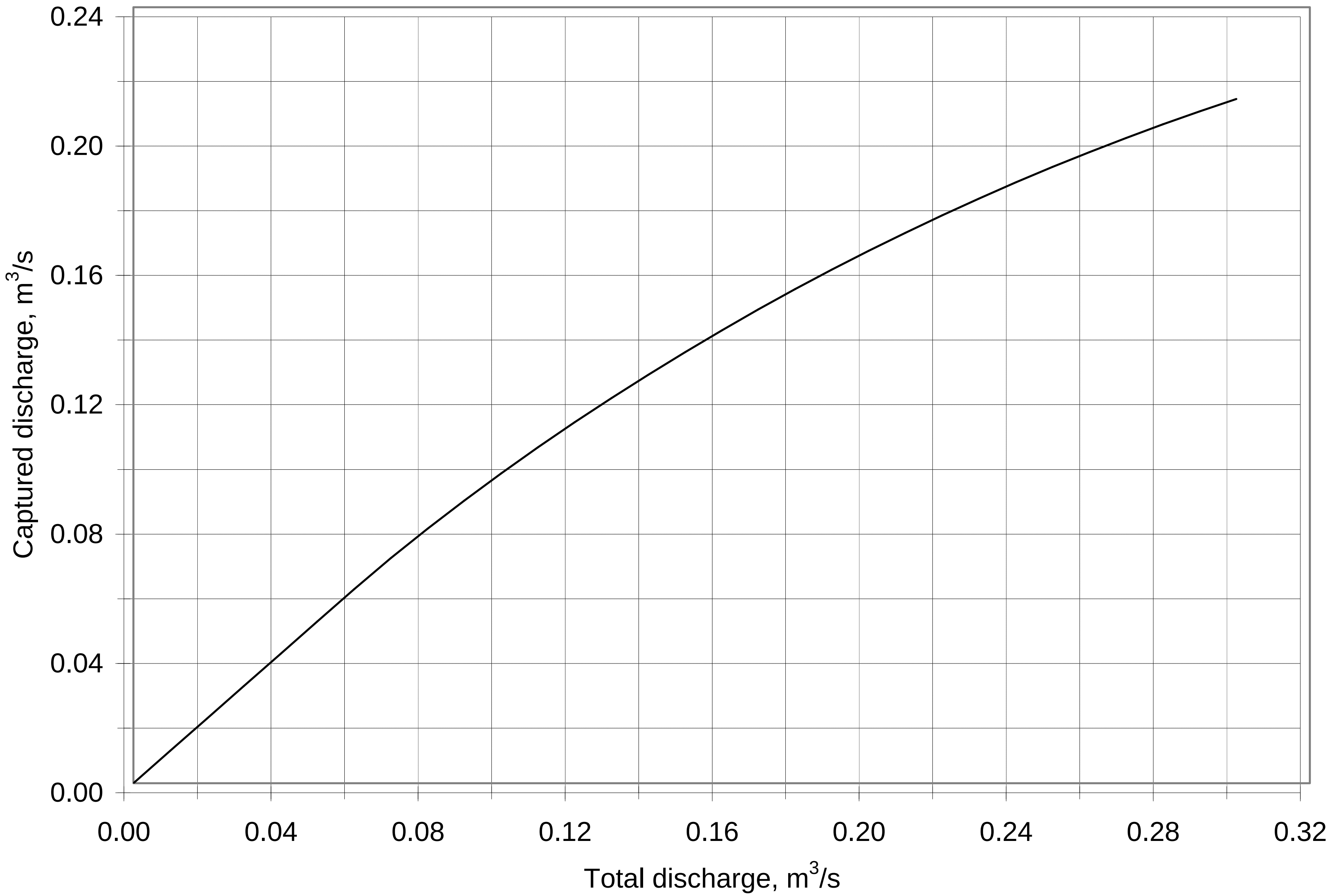

Fig. B.8. Type 22 Curb Inlet, 4.5 m, on Pavement with 3.1% Cross-Slope

Appendix C

Design Charts for Spread of Water on Pavement

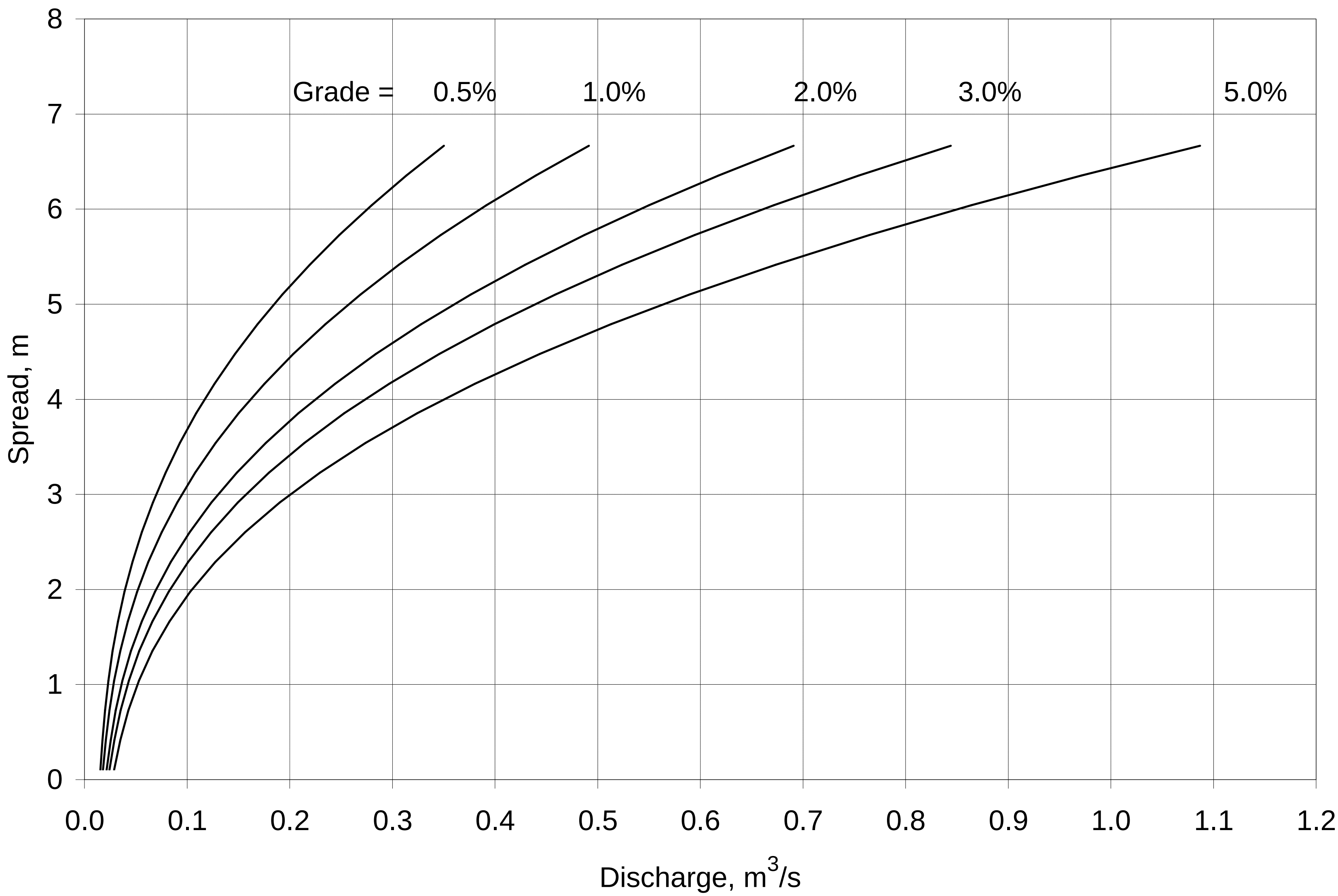

Fig. C.1. Spread on Pavement with 1.6% Cross-Slope and Type I Combined Curb and Gutter

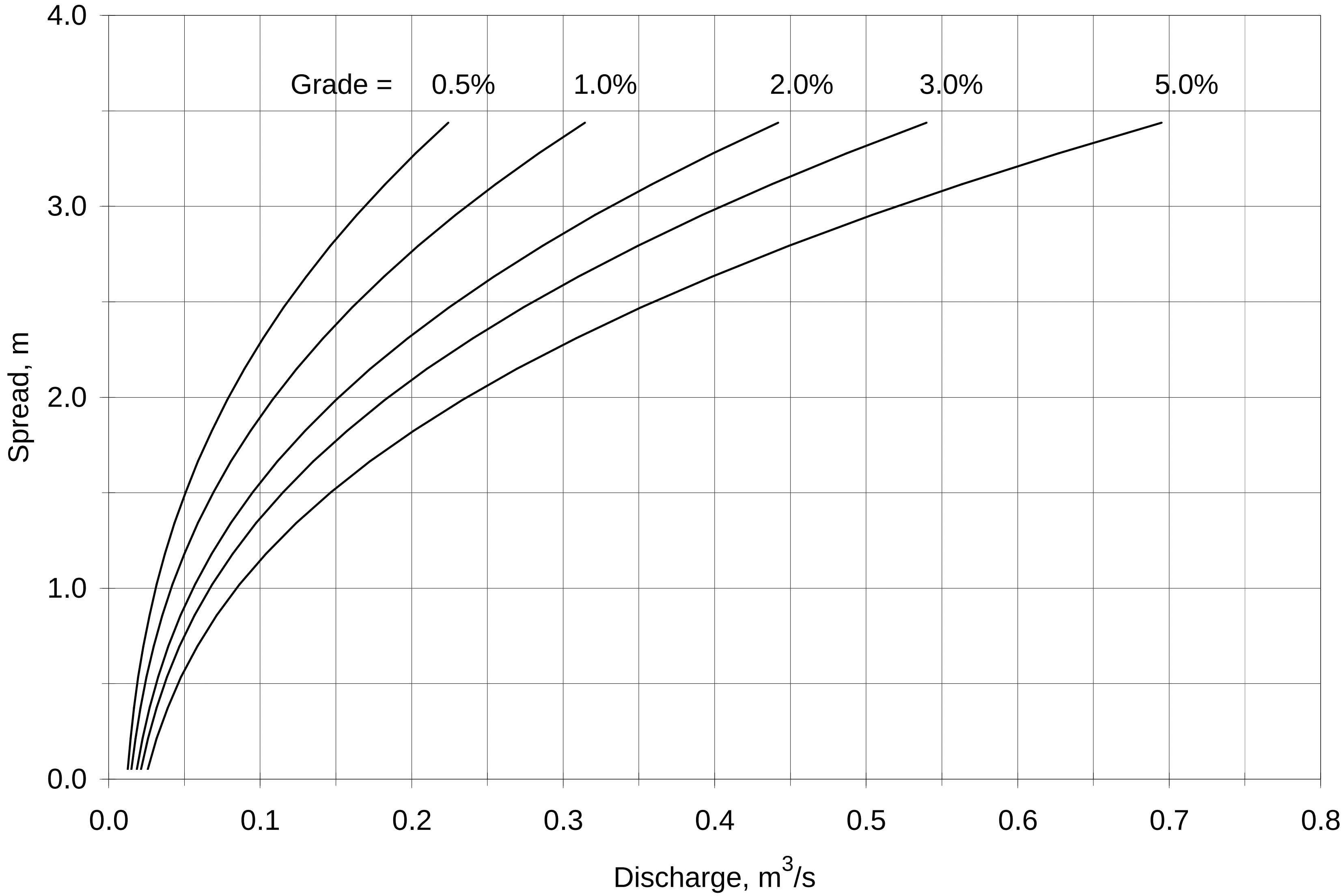

Fig. C.2. Spread on Pavement with 1.6% Cross-Slope and Standard Gutter

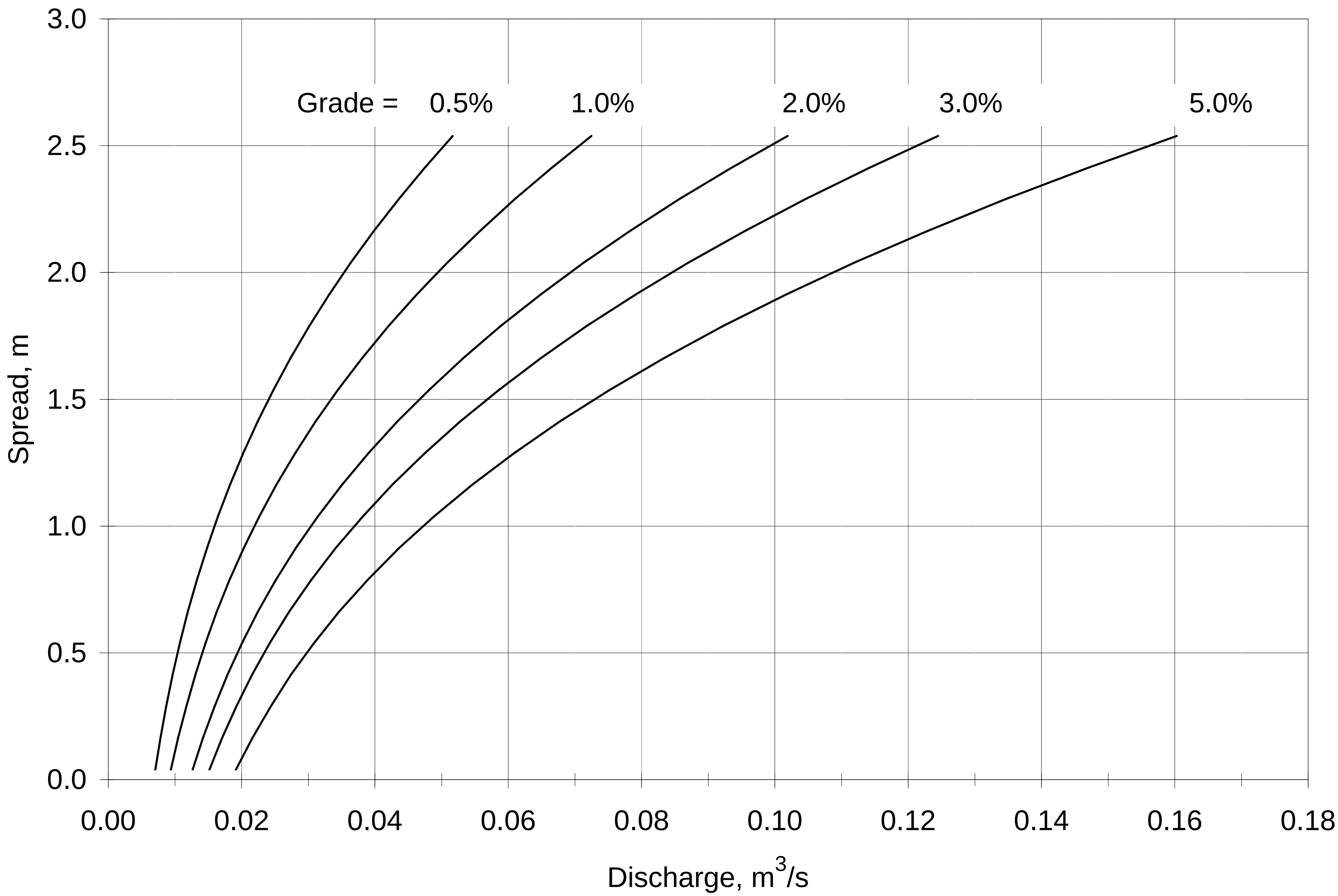

Fig. C.3. Spread on Pavement with 3.1% Cross-Slope and Type I Combined Curb and Gutter

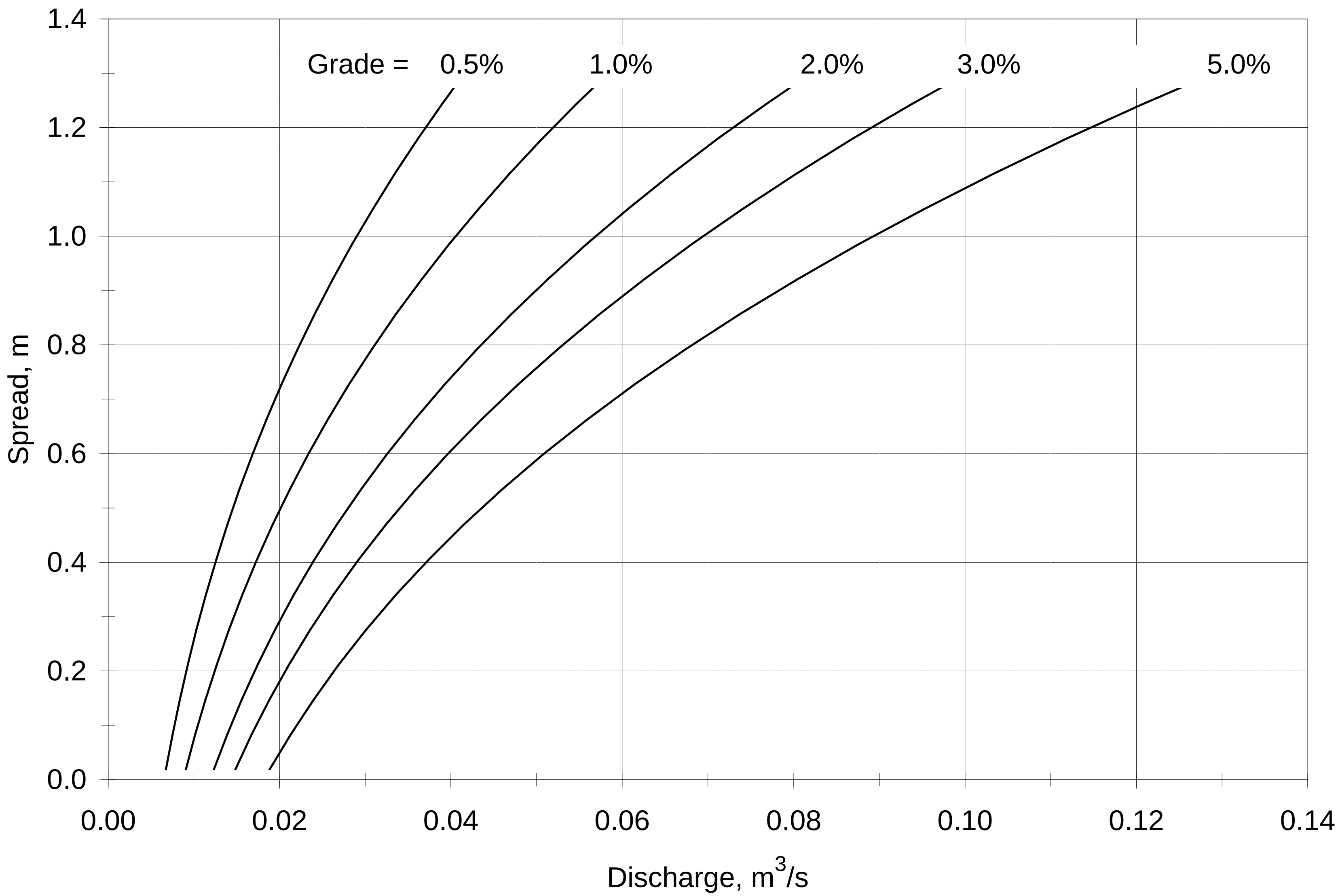

Fig. C.4. Spread on Pavement with 3.1% Cross-Slope and Standard Gutter

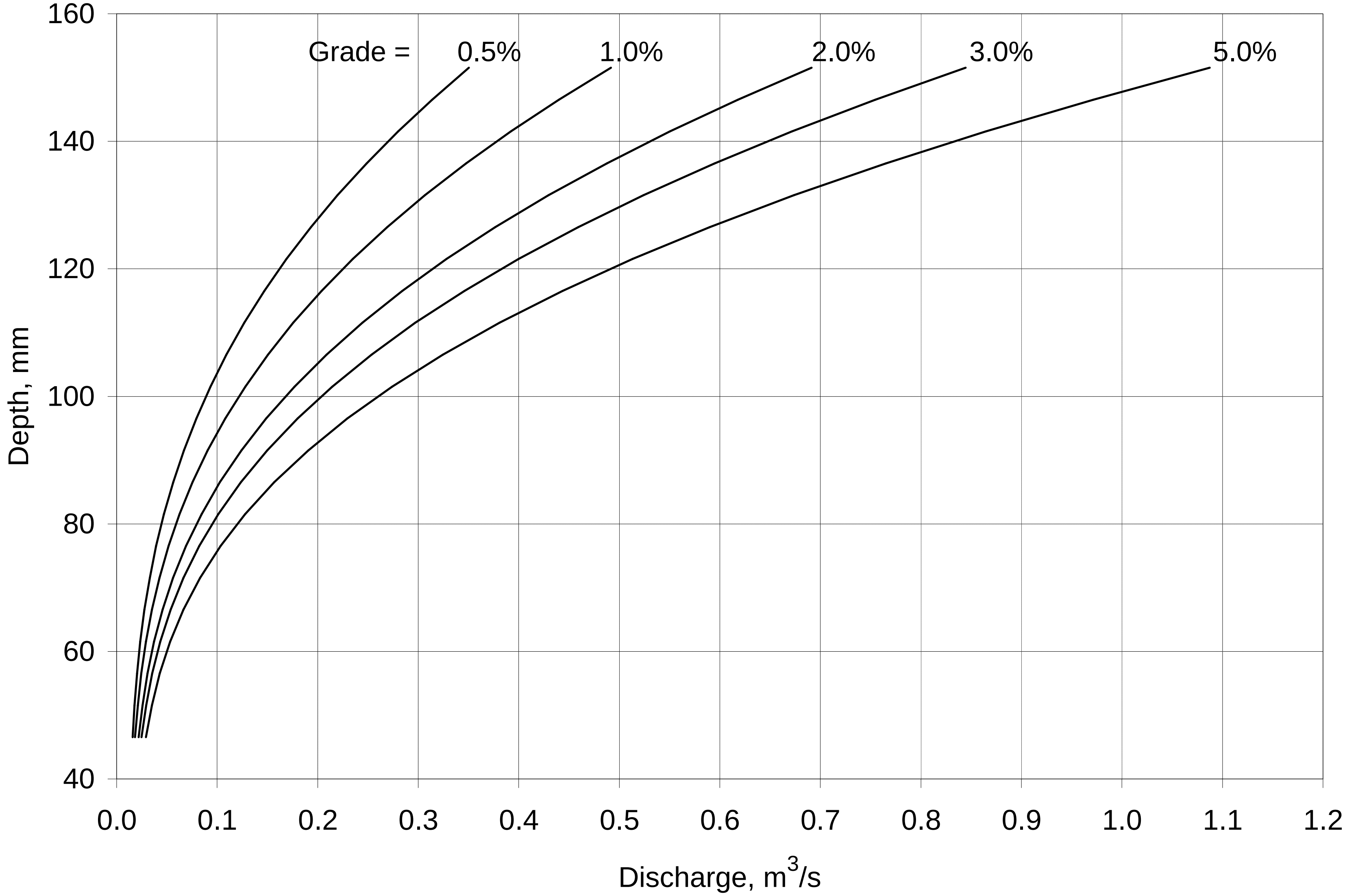

Fig. C.5. Depth of Flow in Type I Combined Curb and Gutter, for Pavement with 1.6% Cross-Slope

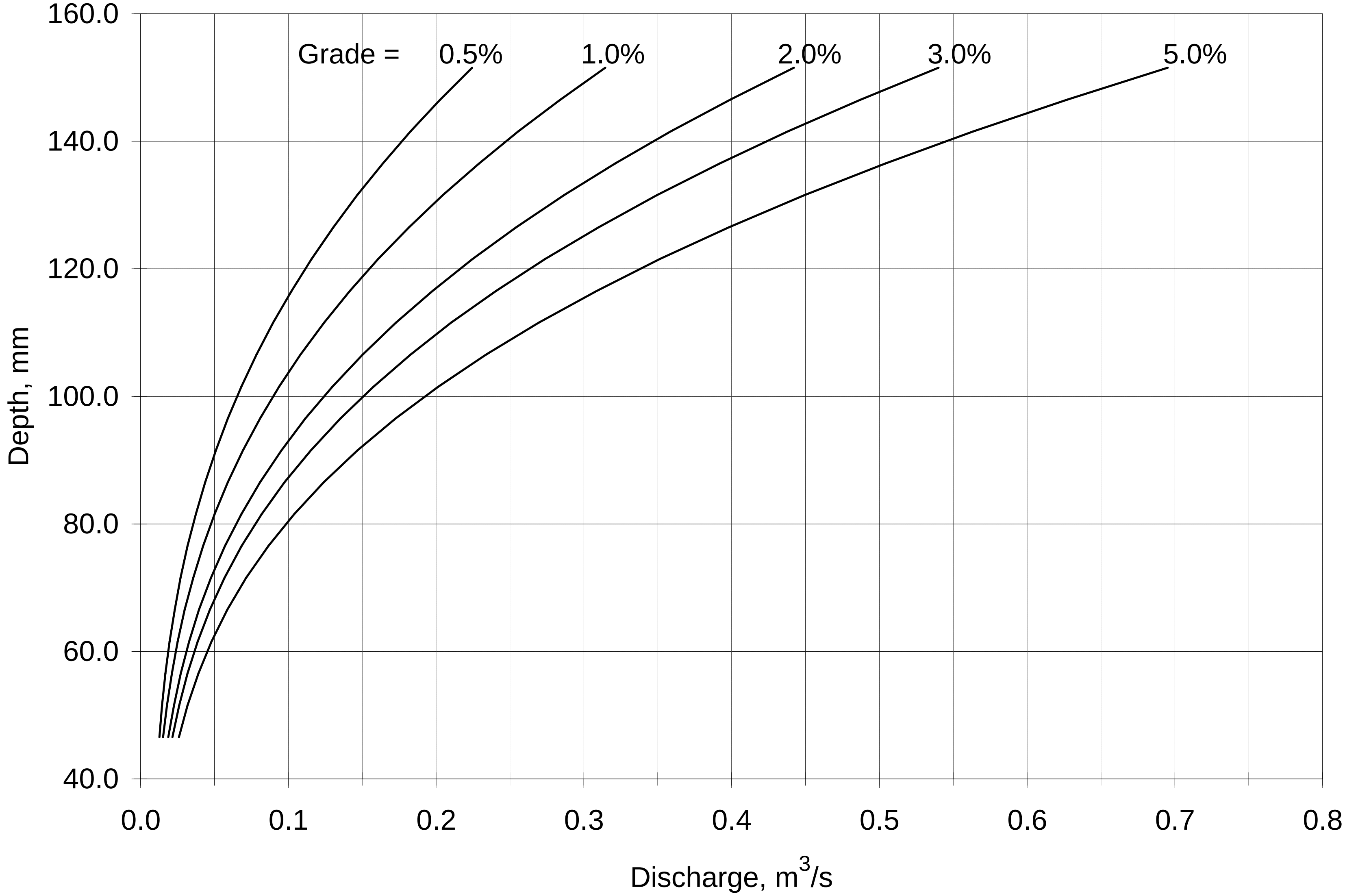

Fig. C.6. Depth of Flow in Standard Gutter, for Pavement with 1.6% Cross-Slope

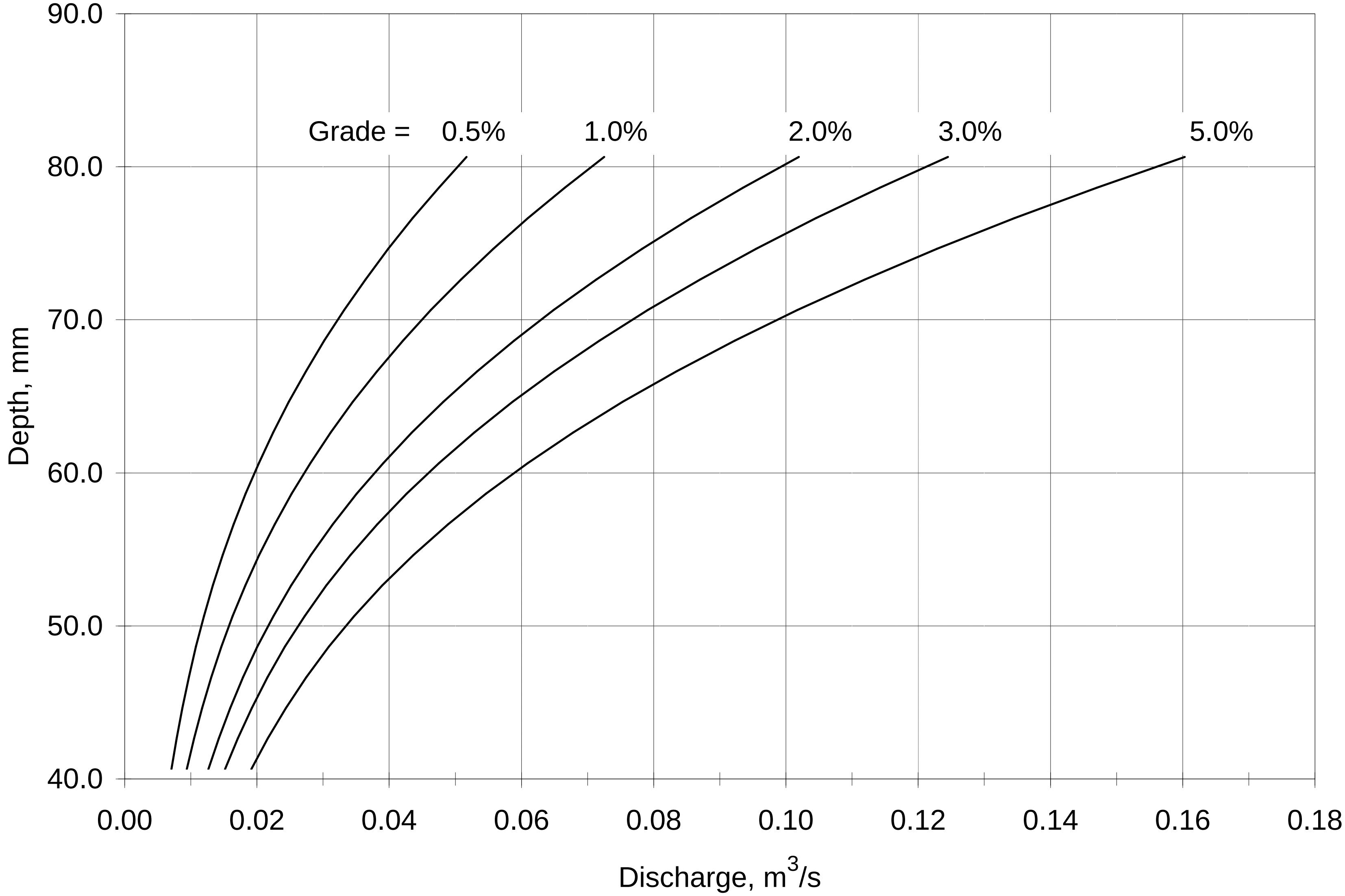

Fig. C.7. Depth of Flow in Type I Combined Curb and Gutter, for Pavement with 3.1% Cross-Slope

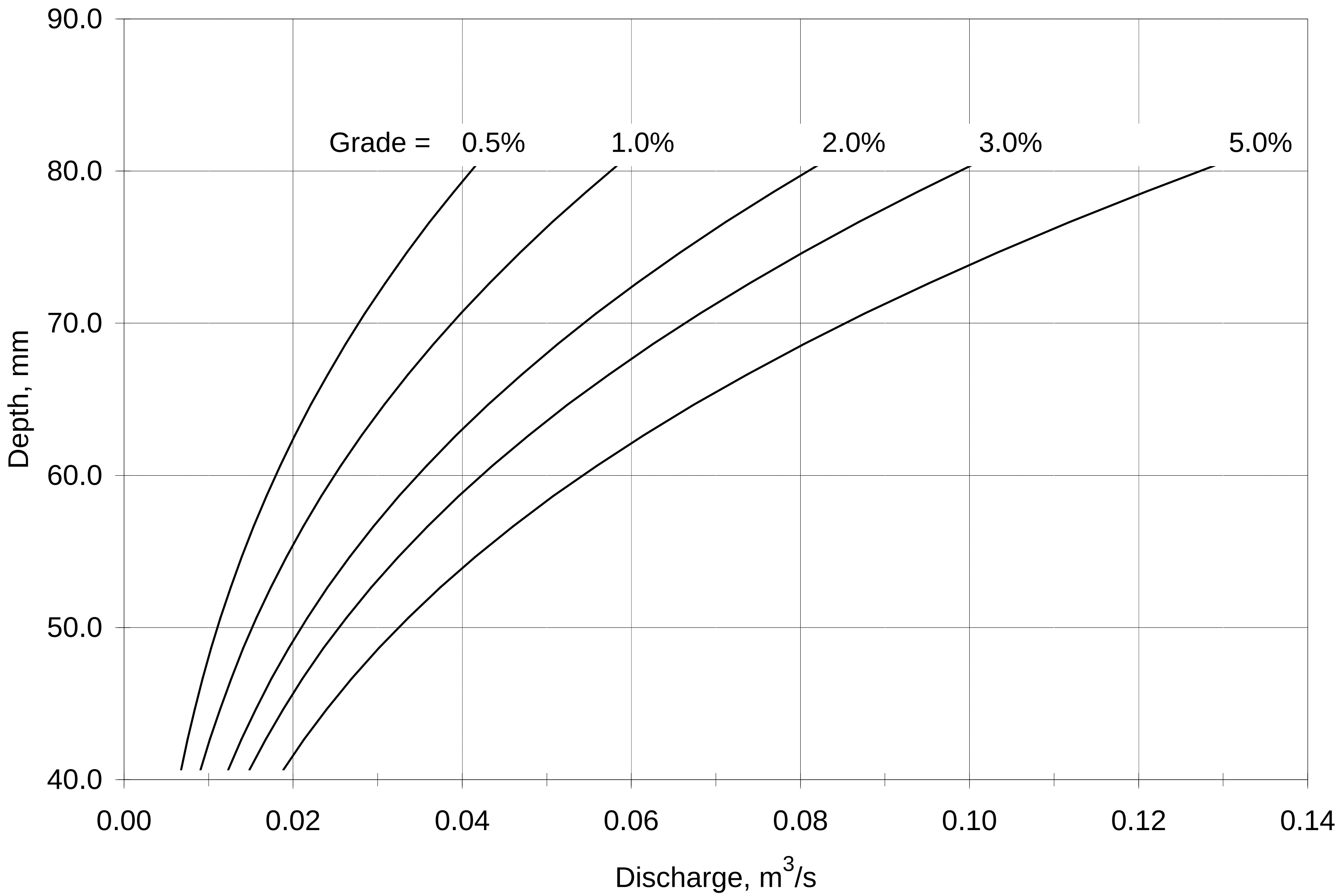

Fig. C.8. Depth of Flow in Standard Gutter, for Pavement with 3.1% Cross-Slope