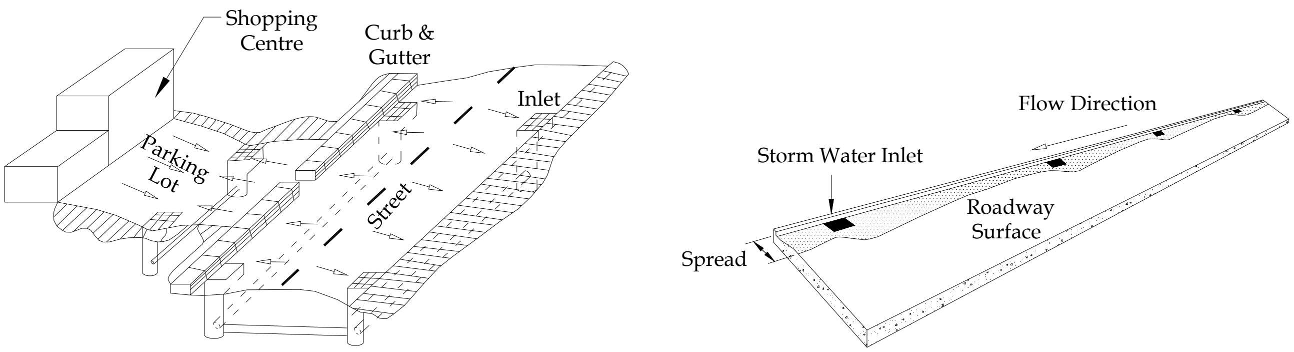
CHAPTER 13 PAVEMENT DRAINAGE

13.1 INTRODUCTION

Effective drainage of pavements is essential to the maintenance of road service levels and to traffic safety. Water on the pavement can interrupt traffic, reduce skid resistance, increase potential for hydroplaning, limit visibility due to splash and spray, and cause difficulty in steering a vehicle when the front wheels encounter puddles. Pavement drainage requires consideration of surface drainage, gutter flow, and inlet capacity (Figure 13.1). The design of these elements is dependent on storm frequency and the allowable spread of stormwater on the pavement surface. This chapter presents guidance for the design of these elements. Most of the information presented are adapted from Hydraulic Engineering Circular No. 22, Third Edition; Urban Drainage Design Manual (FHWA, 2009).



a) Drainage System

b) Variation of Spread

Figure 13.1: Road Drainage Practices

13.2 HYDROPLANING REDUCTION

When rain falls on a sloped pavement surface, it forms a thin film of water that increases in thickness as it flows to the edge of the pavement. This wedge produces a hydrodynamic force which can lift the tyre off the pavement surface or hydroplaning. It has been shown that hydroplaning can occur typically at speeds of 90 km/hr with a water depth of 2mm. The hydroplaning potential of a roadway surface can be reduced by the followings:

- Design the roadway geometries to reduce the drainage path lengths of the water flowing over the pavement; and
- Provide drainage structures along the roadway to capture the flow of water over the pavement.

Table 13.1 provides design ARIs and spreads for different types of road and speeds. They have been set to limit the potential for hydroplaning at high speeds, as well as the potential for vehicles to float or be washed off roads at lower speeds. Risk associated with hydroplaning is high in tropical countries such as Malaysia.

13.3 DESIGN CONSIDERATION

13.3.1 Longitudinal Slope

The recommended minimum values of roadway longitudinal slopes (AASHTO, 1990) will provide safe, acceptable pavement drainage. In addition, the following general guidelines are presented:

- A minimum longitudinal gradient is more important for a curbed pavement than for an uncurbed pavement since the water is constrained by the curb. However, flat gradients on uncurbed pavements can lead to a spread problem if vegetation is allowed to build up along the pavement edge.
- Desirable gutter grades should not be less than 0.5% for curbed pavements with an absolute minimum of 0.3%. Minimum grades can be maintained in very flat terrain by use of a rolling profile, or by warping the cross slope to achieve rolling gutter profiles.

- For adequate drainage in sag vertical curves, a minimum slope of 0.3 percent should be maintained within 15m of the low point of the curve.

Table 13.1: Design ARIs and Spreads (FHWA, 2009)

Road Classification		ARIs	Spread
High Volume or Divided or Bi-directional	< 70 km/hr	10 year	1 m
	> 70 km/hr	10 year	No Spread
	Sag Point	50 year	1 m
Collector	< 70 km/hr	10 year	½ Lane
	> 70 km/hr	10 year	No Spread
	Sag Point	10 year	½ Lane
Local Streets	Low Traffic	5 year	½ Lane
	High Traffic	10 year	½ Lane
	Sag Point	10 year	½ Lane

13.3.2 Cross / Transverse Slope

Table 13.2 presents an acceptable range of cross slopes with various pavement surface types (FHWA, 2009) . These cross slopes are a compromise between the need for reasonably steep cross slopes for drainage and relatively flat cross slopes for driver comfort and safety. In areas of intense rainfall, a somewhat steeper cross slope, at 2.5% may be used to facilitate drainage.

Where three lanes or more are sloped in the same direction, it is desirable to counter the resulting increase in flow depth by increasing the cross slope of the outermost lanes. The two lanes adjacent to the crown line should be pitched at the normal slope, and successive lane pairs, or portions thereof outward, should be increased by about 0.5 to 1%. The maximum pavement cross slope should be limited to 4%.

Table 13.2: Normal Pavement Cross Slopes (FHWA, 2009)

Surface Type	Cross Slope (%)
High-Type Surface	
2 lanes	1.5 – 2.0
3 or more lanes, each direction	1.5 minimum; increase 0.5 to 1.0 per lane; 4.0 maximum
Intermediate Surface	1.5 – 3.0
Low-Type Surface	2.0 – 6.0
Shoulders	
Bituminous or Concrete	2.0 – 6.0
With Curbs	$\geq$ 4.0

Additional guidelines related to cross slope are:

- Although not widely encouraged, inside lanes can be sloped toward the median if conditions warrant;
- Median areas should not be drained across travel lanes;

- The number and length of flat pavement sections in cross slope transition areas should be minimised. Consideration should be given to increasing cross slope in sag vertical curves, crest vertical curves, and in sections of flat longitudinal grades; and
- Shoulders should be sloped to drain away from the pavement, except with raised, narrow medians and superelevations.

13.3.3 Curb and Gutter

Roads in urban areas shall generally be provided with an integral curb and gutter. However, where the volume of gutter flow is negligible as in car parks and on the high side of single-crossfall roads, a curb only is acceptable.

Curbs are normally used at the outside edge of pavement for low-speed, and in some instances adjacent to shoulders on moderate to high-speed roads. They serve the following purposes:

- Containment of the surface runoff within the roadway and away from adjacent properties;
- Prevention of erosion on fill slopes;
- Provision of pavement delineation; and
- Enable the orderly development of property adjacent to the roadway.

Gutters formed in combination with curbs are available in 0.3m through 1.0m width. Gutter cross slopes may be same as that of the pavement or may be designed with a steeper cross slope, usually 80 mm per metre steeper than the shoulder or parking lane (if used). An 8% slope is a common maximum cross slope (FHWA, 2009).

A curb and gutter combination forms a triangular channel that can convey runoff equal to or less than the design flow without interruption of the traffic. When a design flow occurs, there is a spread or widening of the conveyed water surface. The water spreads to include not only the gutter width, but also parking lanes or shoulders, and portions of the travelled surface. Spread is what concerns the hydraulic engineer in curb and gutter flow. The distance of the spread is measured perpendicularly from the curb face to the extent of the water on the roadway and is shown in Figure 13.2.

The curb and gutter shall be a standard size to facilitate economical construction. The standard curb height of 150mm is based upon access considerations for pedestrians, vehicle safety including the opening of car doors, and drainage requirements.

If a local authority decides to adapt a different standard, the design curves given in this chapter will need to be adjusted accordingly.

13.3.4 Roadside and Median Channels

Roadside channels are commonly used with uncurbed roadway sections to convey runoff from the pavement and from areas which drain toward the road. Due to right-of-way limitations, roadside channels cannot be used on most urban arterials. They can be used in cut sections, depressed sections, and other locations where sufficient right-of-way is available and driveways or intersections are infrequent.

To prevent drainage from the median areas from running across the travel lanes, designers should slope median areas and inside shoulders to a center swale. This design is particularly important for high speed roads and for roads with more than two lanes of traffic in each direction.

13.3.5 Median Barriers

Designers should slope the shoulder areas adjacent to median barriers to the center to prevent drainage from running across the traveled pavement. Where median barriers are used, and particularly on horizontal curves with associated superelevations, it is necessary to provide inlets or slotted drains to collect the water accumulated against the barrier. Additionally, some road department agencies use a piping system to convey water through the barrier.

13.4 GUTTER DESIGN

A pavement gutter is defined as a section of pavement of the roadway which conveys storm runoff. It may include a portion or all of a travel lane. Gutter sections can be categorized as conventional or shallow swale type as illustrated in Figure 13.2. Conventional curb and gutter sections usually have a triangular shape with the curb forming the near-vertical leg of the triangle. Shallow swale gutters typically have V-shaped or circular sections and are often used in paved median areas on roadways with inverted crowns.

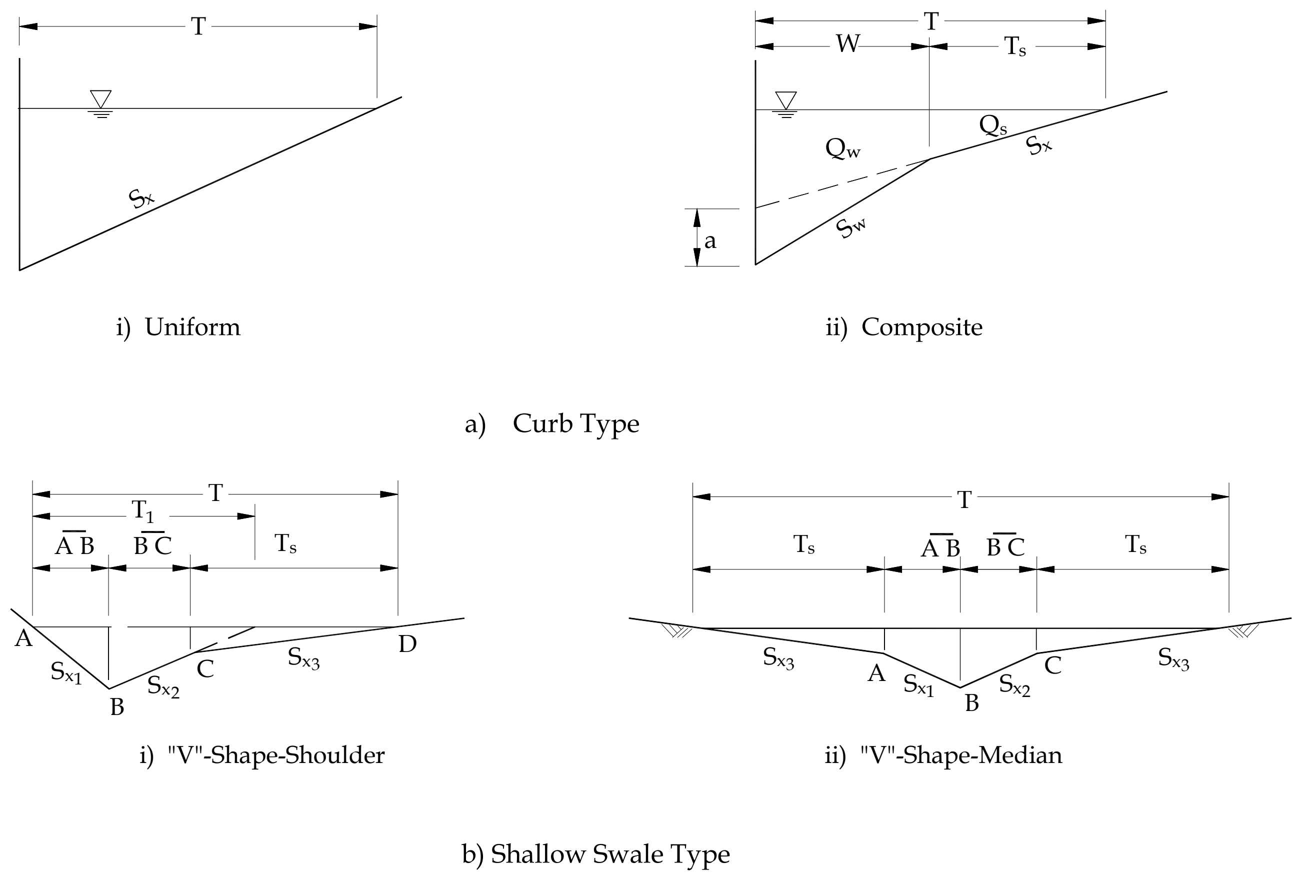


Figure 13.2: Typical Gutter Sections

13.4.1 Capacity Relationship

Gutter flow calculations are necessary to establish the spread of water on the shoulder, parking lane, or pavement section. To compute gutter flow, the Manning's equation is integrated for an increment of width across the section. The resulting equation is:

$$Q = \frac{K_u}{n} S_X^{\,1.67} S_L^{\,0.5} T^{\,2.67} \qquad (13.1)$$

where,

K_u = 0.376
n = Manning's roughness coefficient (Table 13.3);
Q = Flow rate (m³/s);
T = Width of flow or spread (m);
S_X = Cross slope (m/m); and
S_L = Longitudinal slope (m/m)

Spread on the pavement and flow depth at the curb are often used as criteria for spacing pavement drainage inlets. Chart 13.A1 in Appendix 13.A is a nomograph for solving Equation 13.1. The chart can be used for either criterion with the relationship:

$$d = T\,S_X \tag{13.2}$$

where,

d = Depth of flow (m).

Chart 13.A1 can be used for direct solution of gutter flow where the Manning's n value is 0.016. For other values of n (Table 13.3), designers should divide the value of Q_n by n.

Table 13.3: Pavement Roughness Coefficients (FHWA, 2009)

Gutter / Pavement Materials	Manning's Roughness, n
Concrete gutter, troweled finish	0.012
Asphalt pavement:	
Smooth texture	0.013
Rough texture	0.016
Concrete gutter-asphalt pavement:	
Smooth	0.013
Rough	0.015
Concrete pavement:	
Float finish	0.014
Broom finish	0.016

Note:For gutters with small slope, where sediment may accumulate, increase above values of "n" by 0.002

13.4.2 Uniform Cross Slope Gutter Section

The nomograph in Chart 13.A1 solves Equation 13.1 for gutters having triangular cross sections. Example in Appendix 13.B illustrates its use for the analysis of conventional gutters with uniform cross slope.

13.4.3 Composite Gutter Sections

The design of composite gutter sections requires consideration of flow in the depressed segment of the gutter, Q_w. Equation 13.3a, displayed graphically as Chart 13.A2, is provided for use with Equations 13.3b and 13.3c below and Chart 13.A1 to determine the flow in a width of gutter in a composite cross section, W, less than the total spread, T. The procedure for analysing composite gutter sections is demonstrated in Example in Appendix 13.C.

$$E_o = 1 \Bigg/ \left\{ 1 + \frac{S_w / S_x}{\left[1 + \frac{S_w / S_x}{\frac{T}{W} - 1} \right]^{8/3} - 1} \right\} \tag{13.3a}$$

$$Q_w = Q - Q_S \tag{13.3b}$$

$$Q = \frac{Q_S}{1 - E_o} \tag{13.3c}$$

where,

Q_W = Flow rate in the depressed section of the gutter (m³/s);
Q = Gutter flow rate (m³/s);
Q_S = Flow capacity of the gutter section above the depressed section (m³/s);
E_o = Ratio of flow in a chosen width (usually the width of a grate) to total gutter flow *(Q_w/Q)*;

S_W = $S_X + a/W$ (Figure 13.2aii);
S_X = Cross slope (m/m) ; and
a = Gutter depression, (m).

Chart 13.A3 illustrates a design chart for a composite gutter with a 0.60m width section and a 50mm depression at the curb that begins at the projection of the uniform cross slope at the curb face. A series of charts similar to Chart 13.A3 for "typical" gutter configurations can be developed.

13.4.4 Shallow Swale Gutter Sections

Where curbs are not needed for traffic control, a small swale section of circular or V-shape may be used to convey runoff from the pavement. As an example, the control of pavement runoff on fills may be needed to protect the embankment from erosion. Small swale sections may have sufficient capacity to convey the flow to a location suitable for interception.

Chart 13.A1 can be used to compute the flow in a shallow V-shaped section. When using Chart 13.A1 for V-shaped channels, the cross slope, S_X is determined by the following equation:

$$S_X = \frac{S_{X_1} S_{X_2}}{S_{X_1} + S_{X_2}} \tag{13.4}$$

Example in Appendix 13.D demonstrates the use of Chart 13.A1 to analyze a V-shaped shoulder gutter.

13.4.5 Gutter Flow Time

The flow time in gutters is an important component of the time of concentration for the contributing drainage area to an inlet. To find the gutter flow component of the time of concentration, a method for estimating the average velocity in a reach of gutter is needed. The velocity in a gutter varies with the flow rate and the flow rate varies with the distance along the gutter, i.e., both the velocity and flow rate in a gutter are spatially varied. The time of flow can be estimated by use of an average velocity obtained by integration of the Manning's equation for the gutter section with respect to time.

Table 13.4 and Chart 13.A4 can be used to determine the average velocity in triangular gutter sections. In Table 13.4, T_1 and T_2 are the spread at the upstream and downstream ends of the gutter section respectively. T_a is the spread at the average velocity. Chart 13.A4 is a nomograph to solve Equation 13.5 for the velocity in a triangular channel with known cross slope, gutter slope, and spread.

$$V = \frac{K_u}{n} S_L^{0.5} S_X^{0.67} T^{0.67} \tag{13.5}$$

where,

K_u = 0.752; and
V = Velocity in the triangular channel (m/s).

Table 13.4: Spread at Average Velocity in a Reach of Triangle Gutter

Spread Ratio	Value								
T_1/T_2	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
T_a/T_2	0.65	0.66	0.68	0.70	0.74	0.77	0.82	0.86	0.90

13.5 INLET DESIGN

Storm drain inlets are used to collect runoff and discharge it to downstream storm drainage system. Inlets are typically located in gutter sections, paved medians, and roadside and median ditches.

The hydraulic capacity of a storm drain inlet depends upon its geometry as well as the characteristics of the gutter flow. Inlet capacity governs both the rate of water removal from the gutter and the amount of water that can enter the storm drainage system. Inadequate inlet capacity or poor inlet location may cause flooding on the roadway resulting in a hazard to the traveling public.

13.5.1 Inlet Types

Inlets used for the pavement drainage of surfaces can be divided into the following classes:

- Grate inlets;
- Curb-opening inlets;
- Slotted inlets; and
- Combination inlets.

Grate inlets consist of an opening in the gutter or ditch covered by a grate. Curb-opening inlets are vertical openings in the curb covered by a top slab. Slotted inlets consist of a pipe cut along the longitudinal axis with bars perpendicular to the opening to maintain the slotted opening. Combination inlets consist of both a curb-opening inlet and a grate inlet placed in a side-by-side configuration, but the curb-opening may be located in part upstream of the grate. Figure 13.3 illustrates the three (3) major inlets, grate, curb-opening and combination. Slotted drains may also be used with grates and each type of inlet may be installed with or without a depression of the gutter.

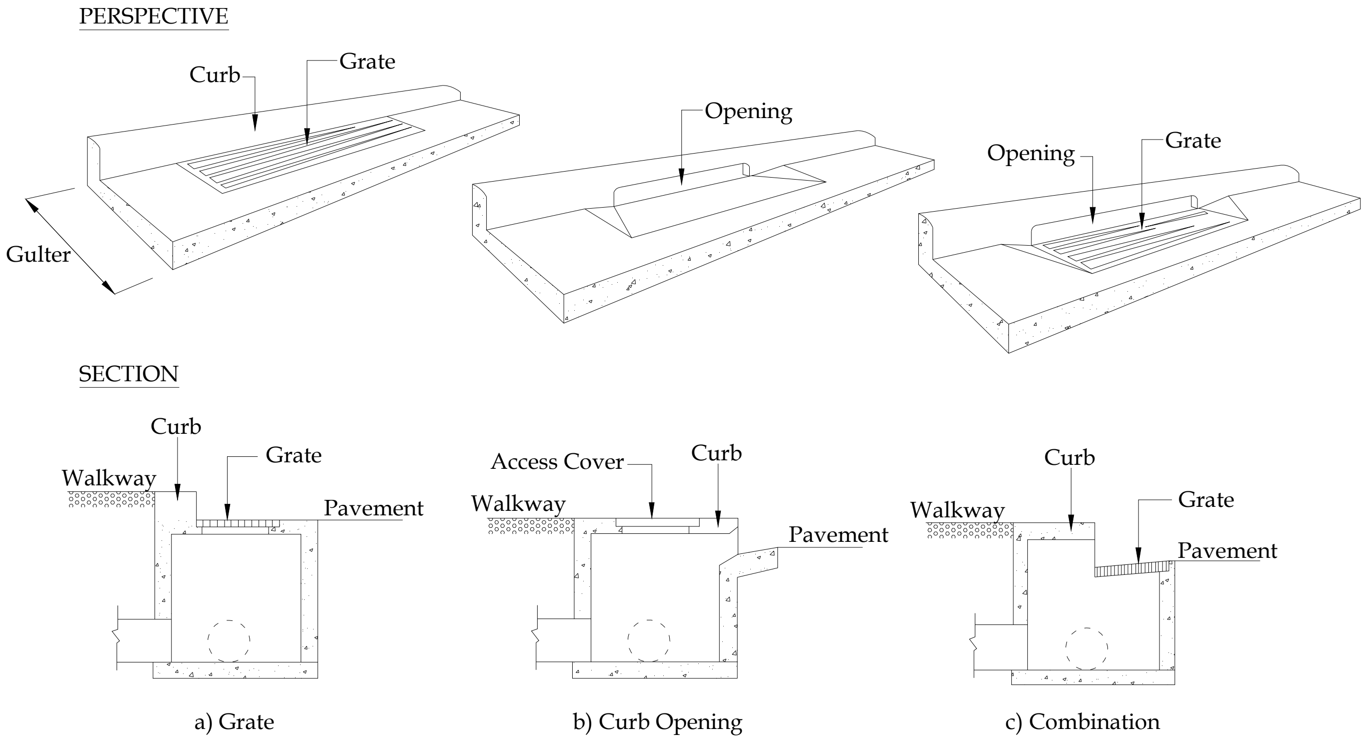


Figure 13.3: Major Inlet Types

13.5.2 Interception Capacity of Inlets on Grade

In this section, design charts for inlets on grade and procedures for using the charts are presented for the various inlet configurations. On-grade inlets that are located in a sloping gutter, so that any flows bypassing the inlet will continue along the gutter flowpath to another inlet downstream or an outfall. For locally depressed inlets, the quantity of flow reaching the inlet would be dependent on the upstream gutter section geometry and not the depressed section geometry.

The chart for frontal flow interception is based on test results which show that grates intercept all of the frontal flow until a velocity is reached at which water begins to splash over the grate. At velocities greater than "splash-over" velocity, grate efficiency in intercepting frontal flow is diminished. Grates also intercept a portion of the flow along the length of the grate, or the side flow. A chart is provided to determine side-flow interception.

One set of charts is provided for slotted inlets and curb-opening inlets, because these inlets are both side-flow weirs. The equation developed for determining the length of inlet required for total interception fits the test data for both types of inlets. A procedure for determining the interception capacity of combination inlets is also presented.

13.5.2.1 Grate Inlets

Grates are effective road pavement drainage inlets where clogging with debris is not a problem. Where clogging may be a problem, see Table 13.5 where grates are ranked for susceptibility to clogging based on laboratory tests using simulated "leaves" (FHWA, 2009). This table should be used for relative comparisons only. When the velocity approaching the grate is less than the "splash-over" velocity, the grate will intercept essentially all of the frontal flow. Conversely, when the gutter flow velocity exceeds the "splash-over" velocity for the grate, only part of the flow will be intercepted. A part of the flow along the side of the grate will be intercepted, dependent on the cross slope of the pavement, the length of the grate, and flow velocity.

Table 13.5: Average Debris Handling Efficiencies of Grates (FHWA, 2009)

Rank	Grate	Longitudinal Slope	
		0.005	0.040
1	Curved Vane	46	61
2	30° 85 Tilt Bar	44	55
3	45° 85 Tilt Bar	43	48
4	P - 50	32	32
5	P – 50 x 100	18	28
6	45° 60 Tilt Bar	16	23
7	Reticuline	12	16
8	P - 30	9	20

The ratio of frontal flow to total gutter flow, E_o, for a uniform cross slope is expressed by Equation 13.6.

$$E_0 = \frac{Q_w}{Q} = 1 - \left[1 - \frac{W}{T}\right]^{2.67} \tag{13.6}$$

where,

Q = Total gutter flow (m³/s);
Q_w = Flow in width W (m³/s);
W = Width of depressed gutter or grate (m); and
T = Total spread of water (m).

The ratio of side flow, Q_s, to total gutter flow, Q is:

$$\frac{Q_S}{Q} = 1 - \frac{Q_{Vw}}{Q} = 1 - E_o \tag{13.7}$$

The ratio of frontal flow intercepted to total frontal flow, R_f, is expressed by Equation 13.8. The value of R_f cannot be more than 1.0

$$R_f = 1 - K_u\,(V - V_o) \tag{13.8}$$

where,

K_u = 0.295;
V = Velocity of flow in the gutter (m/s); and
V_o = Gutter velocity where splash-over first occurs (m/s).

This ratio is equivalent to frontal flow interception efficiency. Chart 13.A5 provides a solution for Equation 13.8 which takes into account grate length, bar configuration, and gutter velocity at which splash-over occurs. The average gutter velocity (total gutter flow divided by the area of flow) is needed to use Chart 13.A5. This velocity can also be obtained from Chart 13.A4. The ratio of side flow intercepted to total side flow, R_S, or side flow interception efficiency, is expressed by Equation 13.9. Chart 13.A6 provides a solution to Equation 13.9.

$$R_S = 1/(1+\frac{K_u V^{1.8}}{S_x L^{2.3}}) \tag{13.9}$$

where,

K_u = 0.0828

A deficiency in developing empirical equations and charts from experimental data is evident in Chart 13.A6. The fact that a grate will intercept all or almost all of the side flow where the velocity is low and the spread only slightly exceeds the grate width is not reflected in the chart. However, the error due to this deficiency is very small. In fact, where velocities are high, side flow interception may be neglected without significant error.

The efficiency, E, of a grate is expressed in Equation 13.10.

$$E = R_f E_o + R_s (1 - E_o) \tag{13.10}$$

The first term on the right side of Equation 13.10 is the ratio of intercepted frontal flow to total gutter flow, and the second term is the ratio of intercepted side flow to total side flow. The second term is insignificant with high velocities and short grates. The interception capacity of a grate inlet on grade is equal to the efficiency of the grate multiplied by the total gutter flow.

$$Q_i = E\,Q = Q\,[R_f E_o + R_s (1 - E_o)] \tag{13.11}$$

13.5.2.2 Curb-Opening Inlets

Curb-opening inlets are effective in the drainage of road pavements where flow depth at the curb is sufficient for the inlet to perform efficiently. Curb openings are less susceptible to clogging and offer little interference to traffic operation. They are a viable alternative to grates on flatter grades where grates would be in traffic lanes or would be hazardous for pedestrians or cyclists.

Curb opening heights vary in dimension, however, a typical maximum height is approximately 100 to 150mm. The length of the curb-opening inlet required for total interception of gutter flow on a pavement section with a uniform cross slope is expressed by Equation 13.12;

$$L_T = K_u Q^{0.42} S_L^{\,0.3} (\frac{1}{nS_X})^{0.6} \tag{13.12}$$

where,

K_u = 0.817
L_T = Curb opening length required to intercept 100 percent of the gutter flow (m);
S_L = Longitudinal slope; and
Q = Gutter flow (m^3/s).

The efficiency of curb-opening inlets shorter than the length required for total interception is expressed by Equation 13.13.

$$E = 1 - (1 - \frac{L}{L_T})^{1.8} \tag{13.13}$$

where,

L = Curb-opening length (m).

Chart 13.A7 is a nomograph for the solution of Equation 13.12, and Chart 13.A8 provides a solution of Equation 13.13.

The length of inlet required for total interception by depressed curb-opening inlets or curb openings in depressed gutter sections can be found by the use of an equivalent cross slope, S_e, in Equation 13.12 in place of S_x and S_e can be computed using Equation 13.14.

$$S_e = S_X + S'_W E_o \tag{13.14a}$$

$$S'_W = a / [1000 W], \text{ for W in m; or } = S_w - S_x; \tag{13.14b}$$

where,

S'_W = Cross slope of the gutter measured from the cross slope of the pavement S_x (m/m);
a = Gutter depression mm; and
E_o = Ratio of flow in the depressed section to total gutter flow determined by the gutter configuration upstream of the inlet.

Figure 13.4 shows the depressed curb inlet for Equation 13.14. E_o is the same ratio as that used to compute the frontal flow interception of a grate inlet.

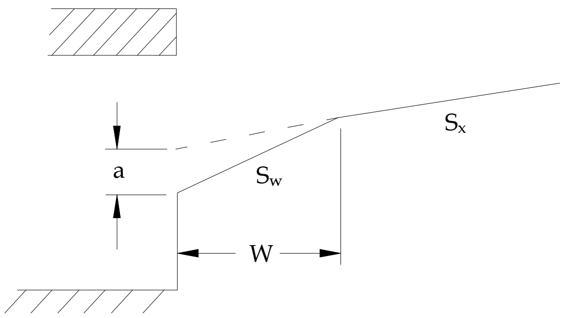


Figure 13.4: Depressed Curb Opening Inlet

As seen from Chart 13.A7, the length of curb opening required for total interception can be significantly reduced by increasing the cross slope or the equivalent cross slope. The equivalent cross slope can be increased by use of a continuously depressed gutter section or a locally depressed gutter section.

Using the equivalent cross slope, S_e, Equation 13.12 becomes,

$$L_T = K_T Q^{0.42} S_L^{0.3} (\frac{1}{nS_e})^{0.6} \tag{13.15}$$

where,

K_T = 0.817.

Equation 13.15 is applicable with either straight cross slopes or composite cross slopes. Charts 13.A7 and 13.A8 are applicable to depressed curb-opening inlets using S_e rather than S_x. Equation 13.14 uses the ratio, E_o, in the computation of the equivalent cross slope, S_e. Example in Appendix 13.E demonstrates the procedure to determine spread and then the example uses Chart 13.A2 to determine E_o. Example in Appendix 13.E demonstrates the use of these relationships to design length of a curb opening inlet.

13.5.2.3 Combination Inlets

The interception capacity of a combination inlet consisting of a curb opening and grate placed side-by-side, as shown in Figure 13.5, is no greater than that of the grate alone. Capacity is computed by neglecting the curb opening.

A combination inlet is sometimes used with a part of the curb opening placed upstream of the grate as illustrated in Figure 13.6. The curb opening in such an installation intercepts debris which might otherwise clog the grate and is called a "sweeper" inlet. A sweeper combination inlet has an interception capacity equal to the sum of the curb opening upstream of the grate plus the grate capacity, except that the frontal flow and thus the interception capacity of the grate is reduced by interception by the curb opening.

Figure 13.5: Combination Curb-opening, 45 Degree Tilt-bar Grate Inlet

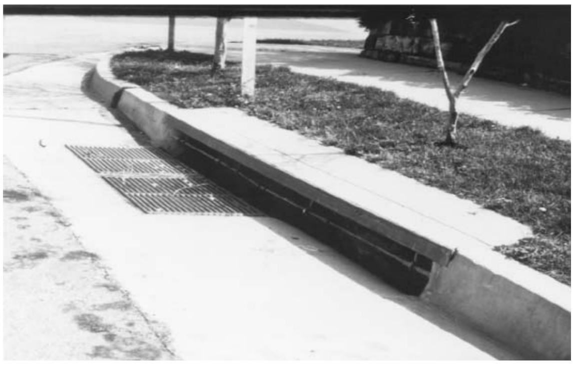


Figure 13.6: Sweeper Combination Inlet

The use of depressed inlets and combination inlets enhances the interception capacity of the inlet. The geometries of the inlets and the gutter slopes were consistent in the examples and Table 13.6 summarizes a comparison of the intercepted flow of the various configurations.

13.5.3 Interception Capacity of Inlets in Sag Location

Inlets in sag locations operate as weirs under low head conditions and as orifices at greater depths. Orifice flow begins at depths dependent on the grate size, the curb opening height, or the slot width of the inlet. At depths between those at which weir flow definitely prevails and those at which orifice prevails, flow is in transition stage. At these depths, control is ill-defined and flow may fluctuate between weir and orifice control. Design procedures presented here are based on a conservative approach to estimate the capacity of inlets in sump locations.

The efficiency of inlets in passing debris is critical in sag locations because all runoff which enter the sag must passed through the inlet. Total or partial clogging of inlets in these locations can result in hazardous ponded conditions. Grate inlets alone are not recommended for use in sag locations because of the tendencies of grates to become clogged. Combination inlets or curb-opening inlets are recommended for use in these locations.

13.5.3.1 Curb-Opening Inlets

The capacity of a curb-opening inlet in sag depends on water depth at the curb, the curb opening length, and the height of the curb opening. The inlet operates as a weir to depths equal to the curb opening height and as an orifice at depths greater than 1.4 times the opening height. At depths between 1.0 and 1.4 times the opening height, flow is in transition stage.

Spread on the pavement is the usual criterion for judging the adequacy of a pavement drainage inlet design. It is also convenient and practical in the laboratory to measure depth at the curb upstream of the inlet at the point of maximum spread on the pavement. Therefore, depth at the curb measurements from experiments coincide with the depth at curb of interest to designers. The weir coefficient for a curb-opening inlet is less than the usual weir coefficient for several reasons, the most obvious of which is that depth measurements from experimental tests were not taken at the weir, and drawdown occurs between the point where measurement were made and the weir.

The weir location for a depressed curb-opening inlet is at the edge of the gutter, and the effective weir length is dependent on the width of the depressed gutter and the length of the curb opening. The weir location for a curb-opening inlet that is not depressed is at the lip of the curb opening, and its length is equal to that of the inlet, as shown in Chart 13.A9.

The equation for the interception capacity of a depressed curb-opening inlet operating as a weir is;

$$Q_i = C_w(L+1.8\ W)\ d^{1.5} \tag{13.16}$$

where,

Q_i = Interception capacity of a grate inlet on grade (m^3/s);
C_W = 1.25;
L = Length of the curb opening (m);
W = Lateral width of depression (m);
d = Depth at curb measured from the normal cross slope (m) i.e., $d = TS_x$.

The weir equation is applicable to depths at the curb approximately equal to the height of the opening plus the depth of the depression. Thus, the limitation on the use of Equation 13.16 for a depressed curb opening inlet is;

$$d \leq h + a/(1000) \tag{13.17}$$

where,

h = Height of curb opening inlet (m); and
a = Depth of depression (mm).

Experiment have not been conducted for curb-opening inlets with a continuously depressed gutter, but it is reasonable to expect that the effective weir length would be as great as that for an inlet in a local depression. Use of Equation 13.16 will yield conservative estimates of the interception capacity.

The weir equation for curb–opening inlets without depression becomes;

$$Q_i = C_w\ L\ d^{1.5} \tag{13.18}$$

Without depression of the gutter section, the weir coefficient, C_w, becomes 1.6. The depth limitation for operation as weir becomes $d \leq h$.

At curb-opening lengths greater than 3.6m, Equation 13.18 for non-depressed inlet produces intercepted flows which exceed the values for depressed inlets computed using Equation 13.16. Since depressed inlets will perform at least as well as non-depressed inlets of the same length, Equation 13.18 should be used for all curb opening inlets having lengths greater than 3.6m.

Curb-opening inlets operate as orifices at depths greater than approximately 1.4 times the opening height. The interception capacity can be computed by Equation 13.19a and Equation 13.19b. These equations are applicable to depressed and undepressed curb-opening inlets. The depth at the inlet includes any gutter depression.

$$Q_i = C_o\, h\, L(2\, g\, d_o)^{0.5} \tag{13.19a}$$

or

$$Q_i = C_o\, A_g\, \{2g[d_i - (h/2)]\}^{0.5} \tag{13.19b}$$

where,

Q_i = Interception capacity of a grate inlet on grade (m^3/s);
C_o = Orifice coefficient (0.67);
d_o = Effective head on the centre of the orifice throat (m);
L = Length of orifice opening (m);
A_g = Clear area of opening (m^2);
d_i = Depth at lip of curb opening (m); and
h = Height of curb opening orifice (m).

The height of the orifice in Equations13.19a and 13.19b assumes as vertical orifice opening. As illustrated in Figure 13.7, other orifice throat locations can change the effective depth on the orifice and the dimension (d_i–$h/2$). A limited throat width could reduce the capacity of the curb-opening inlet by causing the inlet to go into orifice flow at depths less than the heights of the opening.

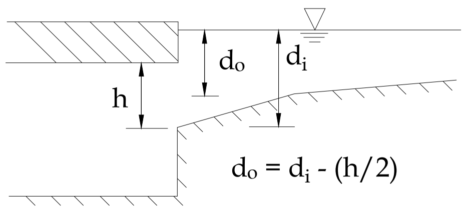


Figure 13.7: Curb-Opening Inlets

Chart 13.A9 provides solutions for Equations 13.16 and 13.19 for depressed curb-opening inlets, and Chart 13.A10 provides solutions for Equations 13.18 and 13.19 for curb-opening inlets without depression.

13.5.3.2 Combination Inlets

Combination inlets consisting of a grate and a curb opening are considered advisable for use in sag where hazardous ponding can occur. Equal length inlets refer to a grate inlet placed along side a curb opening inlet, both of which have the same length. A sweeper inlet refers to a grate inlet placed at the downstream end of a curb opening inlet. The curb opening inlet is longer than the grate inlet and intercepts the flow before the flow reaches the grate. The sweeper inlet is more efficient than the equal length combination inlet and the curb opening has the ability to intercept any debris which may clog the grate inlet. The interception capacity of the equal length combination inlet is essentially equal to that of a grate alone in weir flow. In orifice flow, the capacity of the equal length combination inlet is equal to the capacity of the grate plus the capacity of the curb opening. Equation 13.20 and Chart 13.A11 can be used for grates in weir flow of combination inlets in sag locations.

$$Q_i = C_W\, P\, d^{1.5} \tag{13.20}$$

where,

Q_i = Interception capacity of a grate inlet on grade (m^3/s);
C_W = 1.66;
P = Perimeter of the grate (m); and
d = Average depth across the grate, $0.5(d_1 + d_2)$ (m).

Assuming complete clogging of the grate, Equation 13.16, 13.18, and 13.19 and Charts 13.A9, and 13.A10 for curb opening inlets are applicable.

Where depth at the curb is such that orifice flow occurs, the interception capacity of the inlet is computed by using Equation 13.21:

$$Q_i = 0.67\, A_g\, (2\, g\, d)^{0.5} + 0.67\, h\, L\, (2\, g\, d_o)^{0.5} \tag{13.21}$$

where,

Q_i = Interception capacity of a grate inlet on grade (m^3/s);
A_g = Clear area of the grate (m^2);
g = 9.81 (m/s^2);
d = Average depth over the grate (m);
h = Height of curb opening orifice (m);
L = Length of curb opening (m); and
d_o = Effective depth at the center of the curb opening orifice (m).

13.5.4 Locating Inlets

The location of inlets is determined by geometric controls which require inlets at specific locations, the use and location of flanking inlets in sag vertical curves, and the criterion of spread on the pavement (Figure 13.8). In order to adequately design the location of the inlets for a given project, the following information is needed:

- A layout or plan sheet suitable for outlining drainage areas;
- Road profiles;
- Typical cross sections;
- Grading cross sections;
- Superelevation diagrams; and
- Contour maps.

13.5.4.1 Geometric Controls

There are a number of locations where inlets may be necessary with little regard to contributing drainage area. These locations should be marked on the plans prior to any computations regarding discharge, water spread, inlet capacity, or flow bypass. Examples of such locations follow:

- At all low points in the gutter grade;
- Immediately upstream of median breaks, entrance/exit ramp gores, cross walks, and street intersections., i.e., at any location where water could flow onto the travelway;
- Immediately upgrade of bridges (to prevent pavement drainage from flowing onto bridge decks);
- Immediately downstream of bridges (to intercept bridge deck drainage);
- Immediately up grade of cross slope reversals;
- Immediately up grade from pedestrian cross walks;
- At the end of channels in cut sections;
- On side streets immediately up grade from intersections; and
- Behind curbs, shoulders or sidewalks to drain low area.

In addition to the areas identified above, runoff from areas draining towards the highway pavement should be intercepted by roadside channels or inlets before it reaches the roadway. This applies to drainage from cut

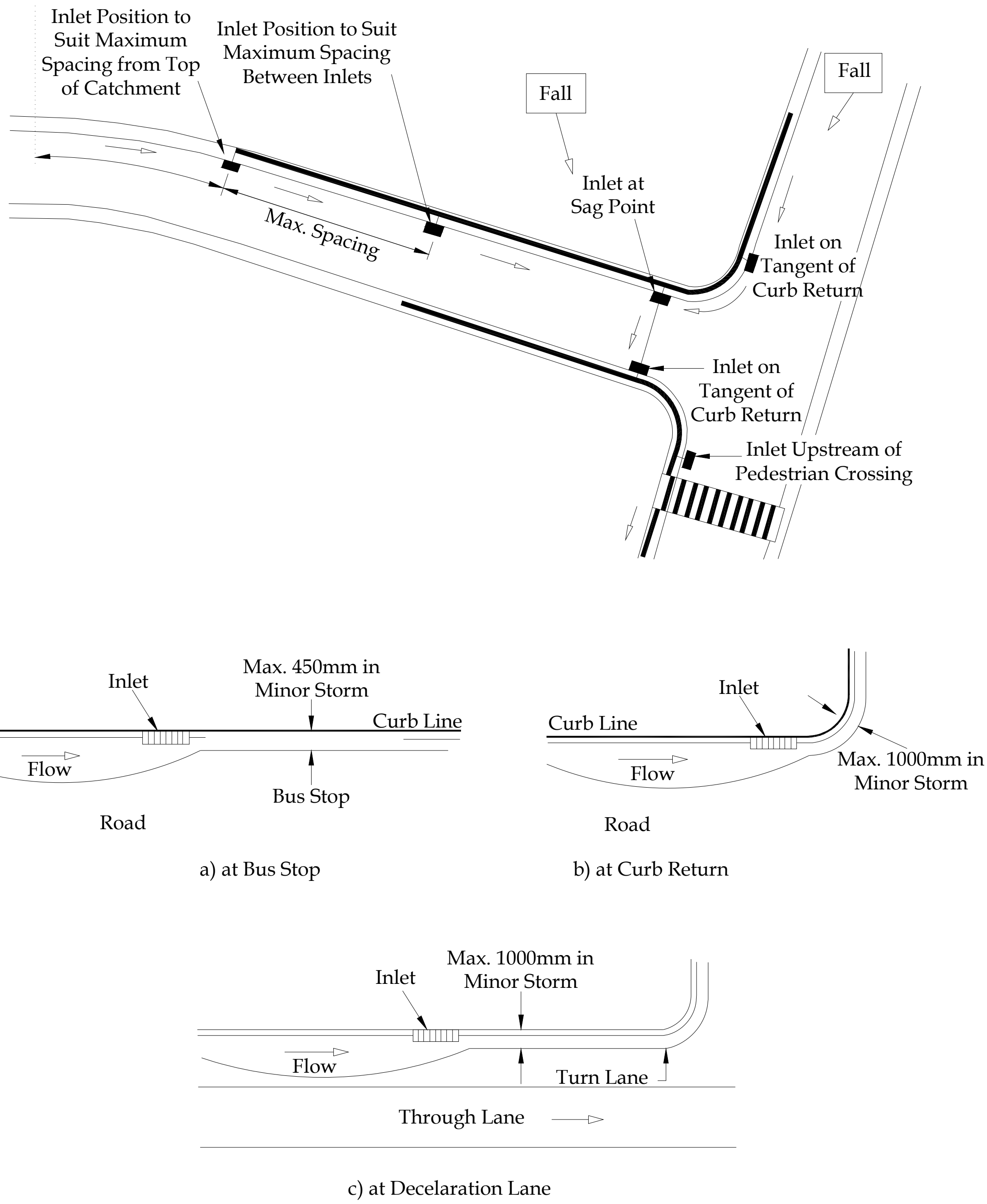


Figure 13.8: Typical Location of Inlet on Roads

slopes, side streets, and other areas alongside the pavement. Curbed pavement sections and pavement drainage inlets are inefficient means of handling extraneous drainage.

13.5.4.2 Inlet Spacing on Continuous Grades

Design spread is the criterion used for locating storm drain inlets between those required by geometric or other controls. The interception capacity of the upstream inlet will define the initial spread. As flow is contributed to the gutter section in the downstream direction, spread increases. The next downstream inlet is located at the point where the spread in the gutter reaches the design spread. Therefore, the spacing of inlets on a continuous grade is a function of the amount of upstream bypass flow, the tributary drainage area, and the gutter geometry.

For a continuous slope, the designer may establish the uniform design spacing between inlets of a given design if the drainage area consists of pavement only or has reasonably uniform runoff characteristics and is rectangular in shape. In this case, the time of concentration is assumed to be the same for all inlets. The following procedure and example illustrate the effects of inlet efficiency on inlet spacing.

13.5.5 Inlet Spacing Design Procedure

In order to design the location of inlets on a continuous grade, the computation sheet shown in Table 13.6 may be used to document the analysis. A step by step procedure for the use of Table 13.6 is presented as follows:-

Step 1: Complete the blanks at the top of the sheet to identify the job by state project number, route, date, and your initials.

Step 2: Mark on a plan the location of inlets which are necessary even without considering any specific drainage area, such as the locations described in Section 13.5.4.1.

Step 3: Start at a high point, at one end of the job if possible, and work towards the low point. Then begin at the next high point and work backwards toward the same low point.

Step 4: To begin the process, select a drainage area below the highest point and outline the area on the plan. Include any area that drain over the curb, onto the roadway.

Step 5: Describe the location of the proposed inlet by number and station and record this information in Columns 1 and 2. Identify the curb and gutter type in Column 19 (Remarks). A sketch of the cross section should be prepared.

Step 6: Compute the drainage area (hectares) outlined in Step 4 and record this in Column 3.

Step 7: Determine the runoff coefficient, C, for the drainage area. Select a C value provided in Table 2.5 and record the value in Column 4.

Step 8. Compute the time of concentration, t_c, in minutes, for the first inlet and record in Column 5. The minimum time of concentration is 5 minutes.

Step 9: Using the time of concentration, determine the rainfall intensity from the Intensity-Duration-Frequency (IDF) curve for the design frequency. Enter the value in Column 6.

Step10: Calculate the flow in the gutter using Equation 2.3, $Q=CIA/K_c$. The flow is calculated by multiplying Column 3 times Column 4 times Column 6 divided by K_c. Using the SI system of units, $K_u = 360$. Enter the flow value in Column 7.

Step 11: From the roadway profile, enter in Column 8 the gutter longitudinal slope, S_L, at the inlet, taking into account any superelevation.

Step12: From the cross section, enter the cross slope, S_x, in Column 9 and the grate or gutter width, W, in Column 13.

Step13: For the first inlet in a series, enter the value from Column 7 into Column 11, since there was no previous bypass flow. Additionally, if the inlet is the first in a series, enter 0 into Column10.

Step14: Determine the spread, T, by using Equations 13.1 and 13.3a or Charts 13.A1 and enter, the value in Column 14. Also, determine the depth at the curb, d, by multiplying the spread by the appropriate cross slope, and enter the value in Column 12. Compare the calculated spread with the allowable spread as determined by the design criteria outlined in Table 13.1. Additionally, compare the depth at the curb with the actual curb height in Column 19. If the calculated spread, Column 14, is near the allowable spread and the depth at the curb is less than the actual curb height, continue on to Step 15. Else, expand or decrease the drainage area up to the first inlet to increase or decrease the spread, respectively. The drainage area can be expanded by increasing the length to the inlet and it can be decreased by decreasing the distance to the inlet. Then, repeat Steps 6 through 14 until appropriate values are obtained.

Step 15: Calculate W/T and enter the value in Column 15.

Step 16: Select the inlet type and dimensions and enter the values in Column 16.

Step 17: Calculate the flow intercepted by the grate, Q_i, and enter the value in Column 17. Use Equations 13.6 and 13.5 or Charts 13.A2 and 13.A4 to define the gutter flow. Use Chart 13.A5 and Equation 13.9 or Chart 13.A6 to define the flow intercepted by the grate. Use Equations 13.12 and 13.13 or Charts 13.A7 and 13.A8 for curb opening inlets. Finally, use Equation 13.11 to determine the intercepted flow.

Step 18: Determine the bypass flow, Q_b, and enter into Column 18. The bypass flow is the value in Column 11 minus that in Column 17.

Step 19: Proceed to the next inlet down the grade. To begin the procedure, select a drainage area appropriately. Repeat Steps 5 through 7 considering only the area between the inlets, entering values in Columns 1 to 4.

Step 20: Compute the time of concentration for the next inlet based upon the area between the consecutive inlets and record this value in Column 5.

Step 21: Determine the rainfall intensity from the IDF curve based upon the time of concentration determined in Step 19 and record the value in Column 6.

Step 22: Determine the flow in the gutter by using Equation 2.3 and record the value in Column 7.

Step 23: Record the value from Column 18 of the previous line into Column 10 of the current line. Determine the total gutter flow by adding Column 7 and Column 10 and record this in Column 11.

Step 24: Determine the spread and the depth at the curb as outlined in Step 14, entering the depth in Column 12 and the spread in Column 14. Repeat Steps 18 through 24 until the spread and the depth at the curb are within the design criteria.

Step 25: Select the inlet type and record this in Column 16.

Step 26: Determine the intercepted flow in accordance with Step 17, entering this in Column 17.

Step 27: Calculate the bypass flow by subtracting Column 17 from Column 11. Enter this in Column 18. This completes the spacing design for the inlet.

Step 28: Repeat Steps 19 through 27 for each subsequent inlet down to the low point.

Example in Appendix 13.F illustrates the use of this procedure, referring to Table 13.6.

Table 13.6: Inlet Spacing Computation Worksheet

INLET SPACING COMPUTATION SHEET												Date : Computed By:		Route/Location : Sheet 1 of 1				
Inlet		Gutter Discharge Design Frequency					Gutter Discharge Allowable Spread								Inlet Discharge			
No. (1)	Station (2)	Drainage Area(ha)(3)	Runoff Coefficient, C (4)	Time of Concentration, t_c (min) (5)	Rainfall Intensity, *i* (mm/hr) (6)	$Q = CIA/K_c$ (m^3/s) (7)	Longitudinal Slope, S_L (m/m) (8)	Cross Slope, S_x or S_w (m/m) (9)	Previous By-pass Flow (m^3/s)(10)	Total Gutter Flow (m^3/s)(11)	Depth, d (m) (12)	Grate or Gutter Width, W (m) (13)	Spread, T (m)(14)	W/T (15)	Inlet Type (16)	Intercept Flow, Q_i (m^3/s)(17)	By-pass Flow, Q_b (m^3/s) (18)	Remarks (19)

REFERENCES

1. American Association of State Highway and Transportation Officials, AASHTO (1990). *Policy on Geometric Design* . Washington DC.
2. American Association of State Highway and Transportation Officials, AASHTO (1987). *Drainage Handbook.* Washington DC.
3. U.S. Federal Highway Administration (2009). *Urban Drainage Design Manual.* U.S. Department of Transportation, Washington DC.

APPENDIX 13.A DESIGN CHARTS

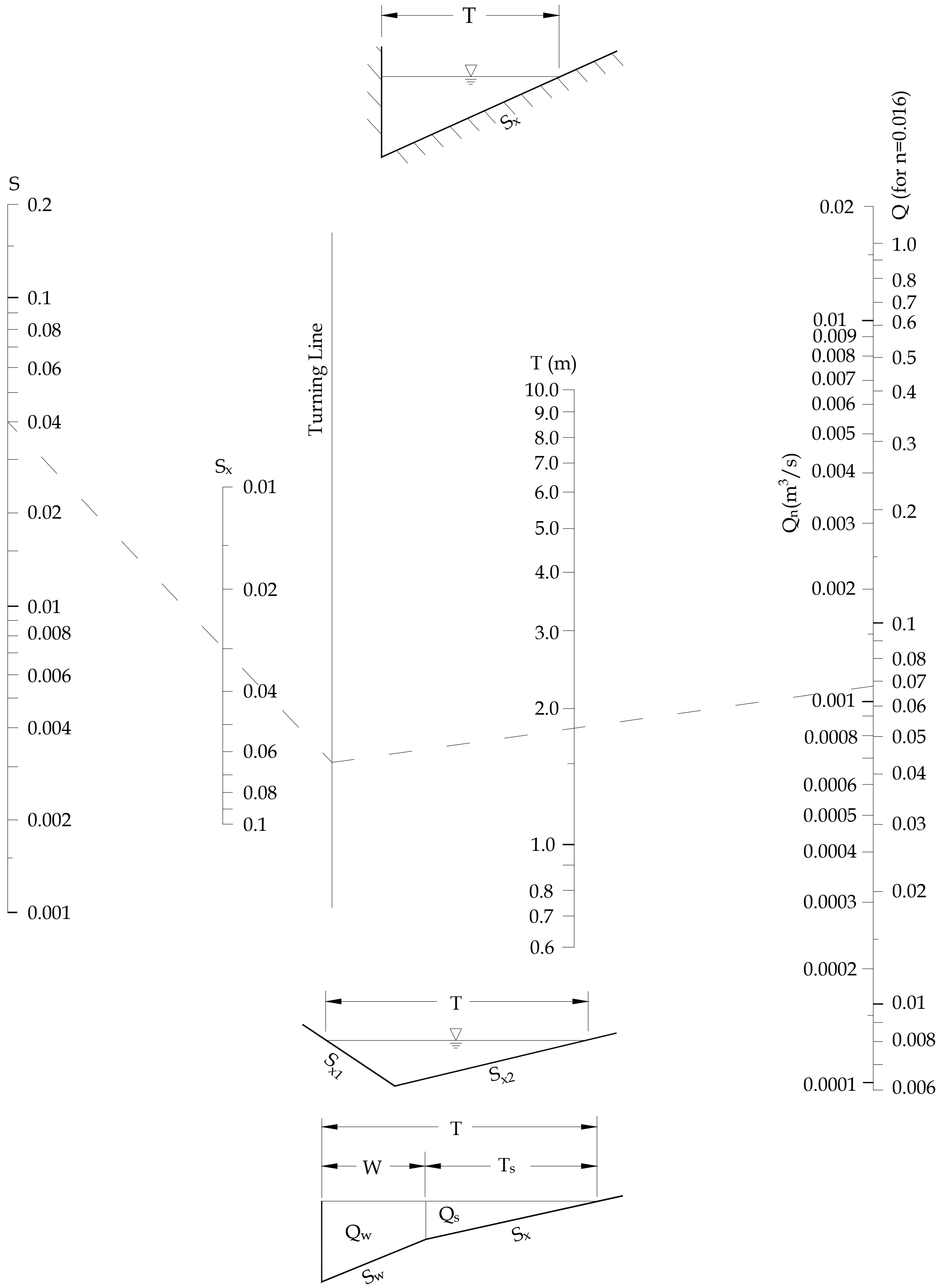


Chart 13.A1: Flow Estimation in Triangular Gutter Section (FHWA, 2009)

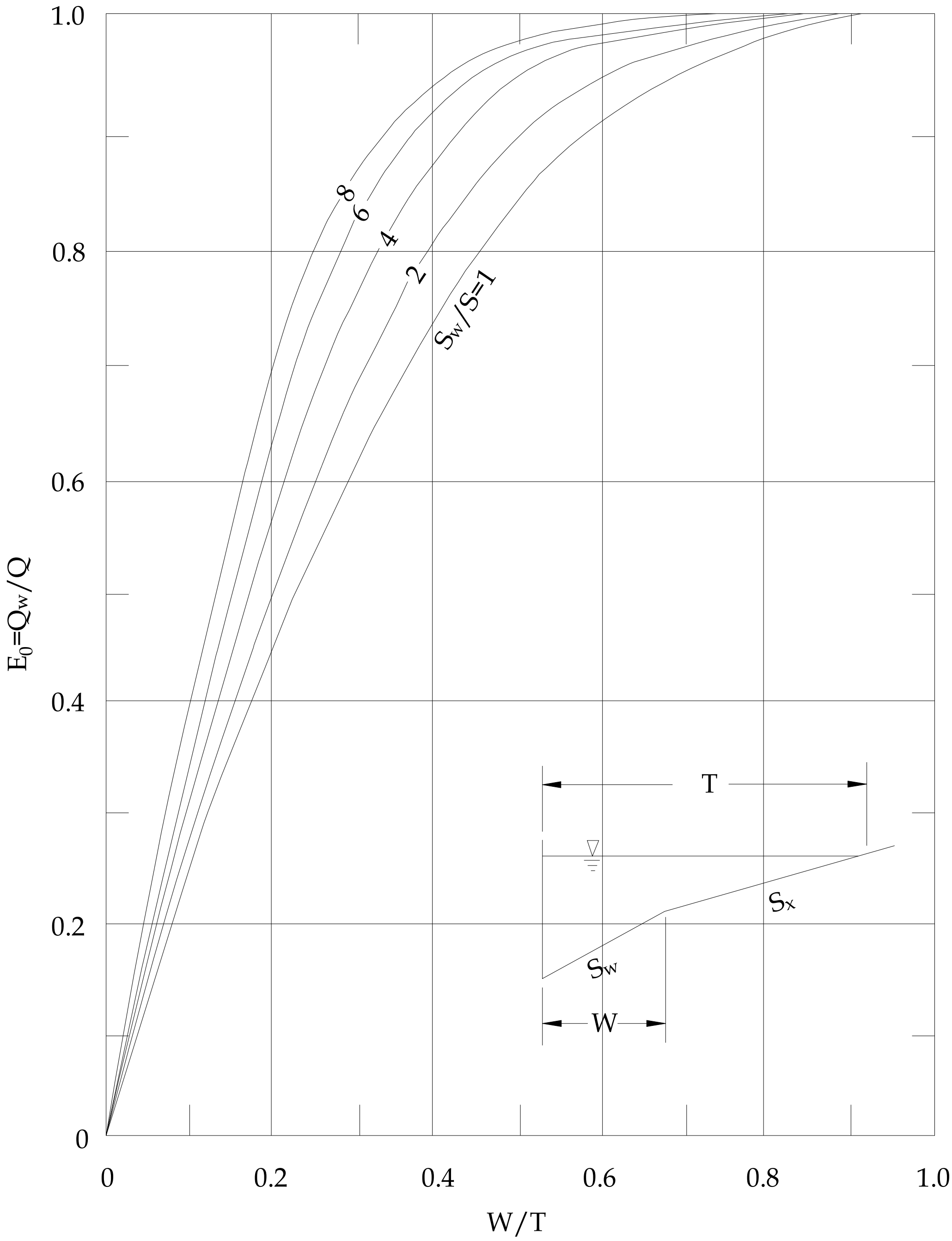


Chart 13.A2: Ratio of Frontal Flow to Total Gutter Flow (FHWA, 2009)

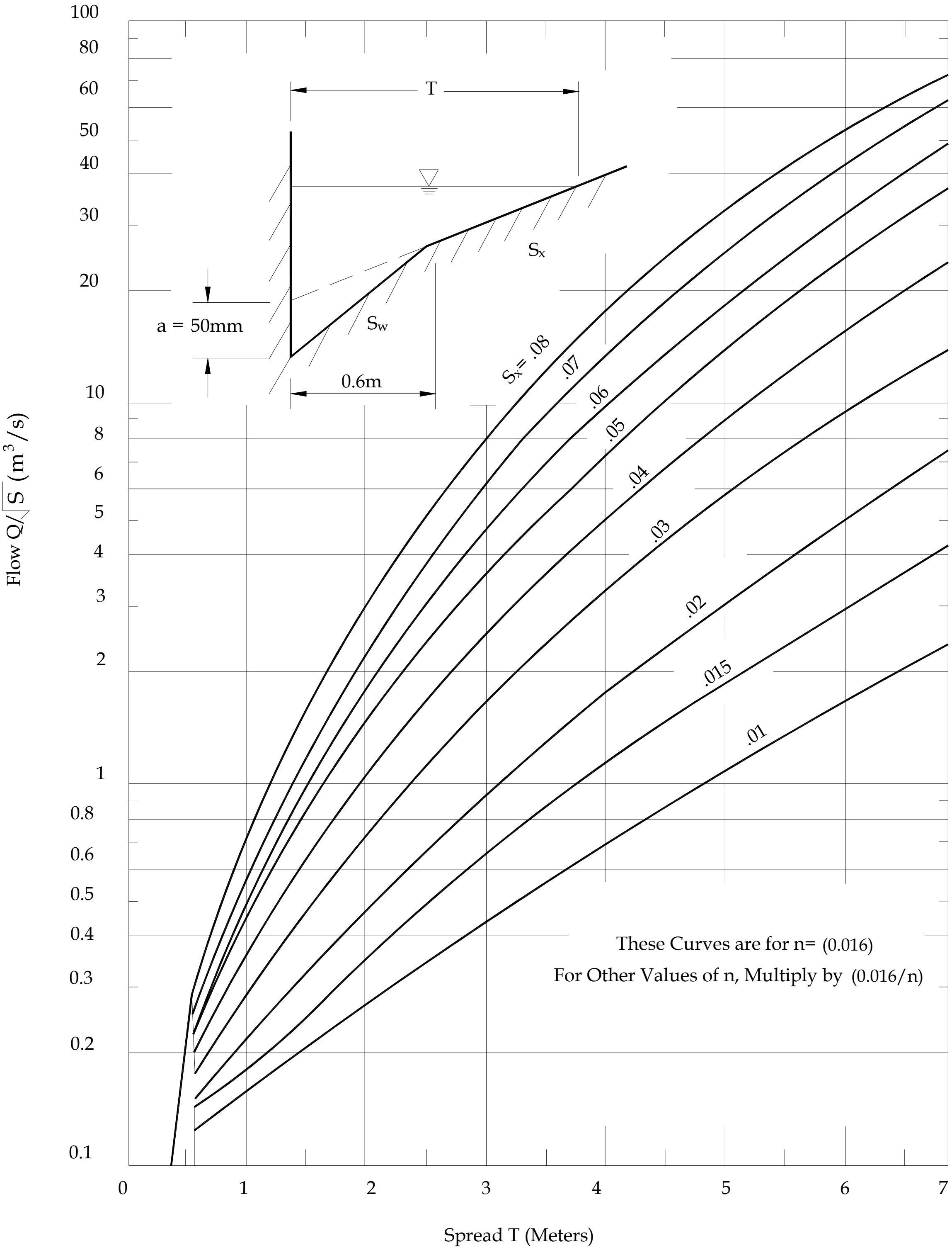


Chart 13.A3: Conveyance – Spread Curves for a Composite Gutter Section (FHWA, 2009)

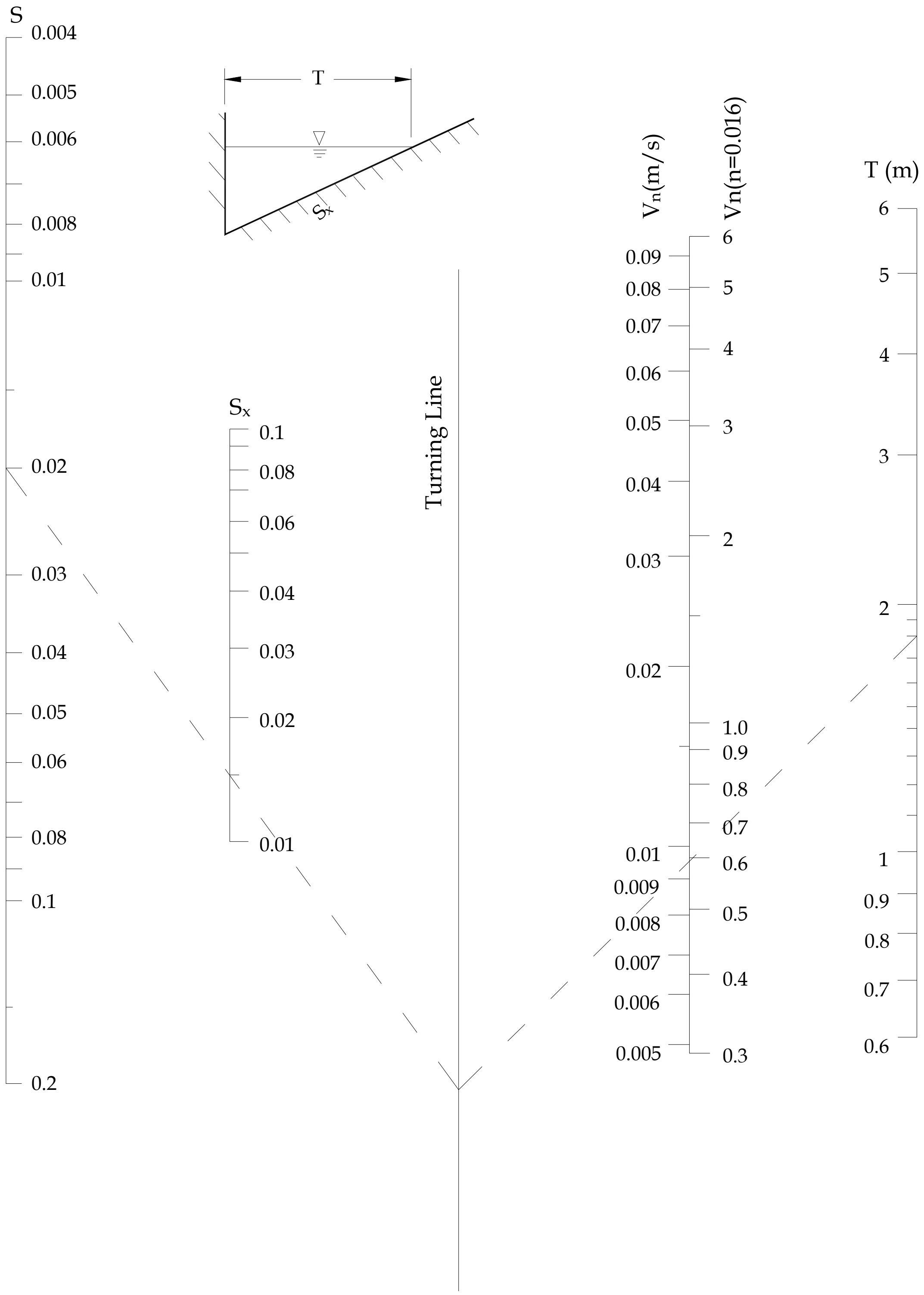


Chart 13.A4: Velocity in Triangular Gutter Sections (FHWA, 2009)

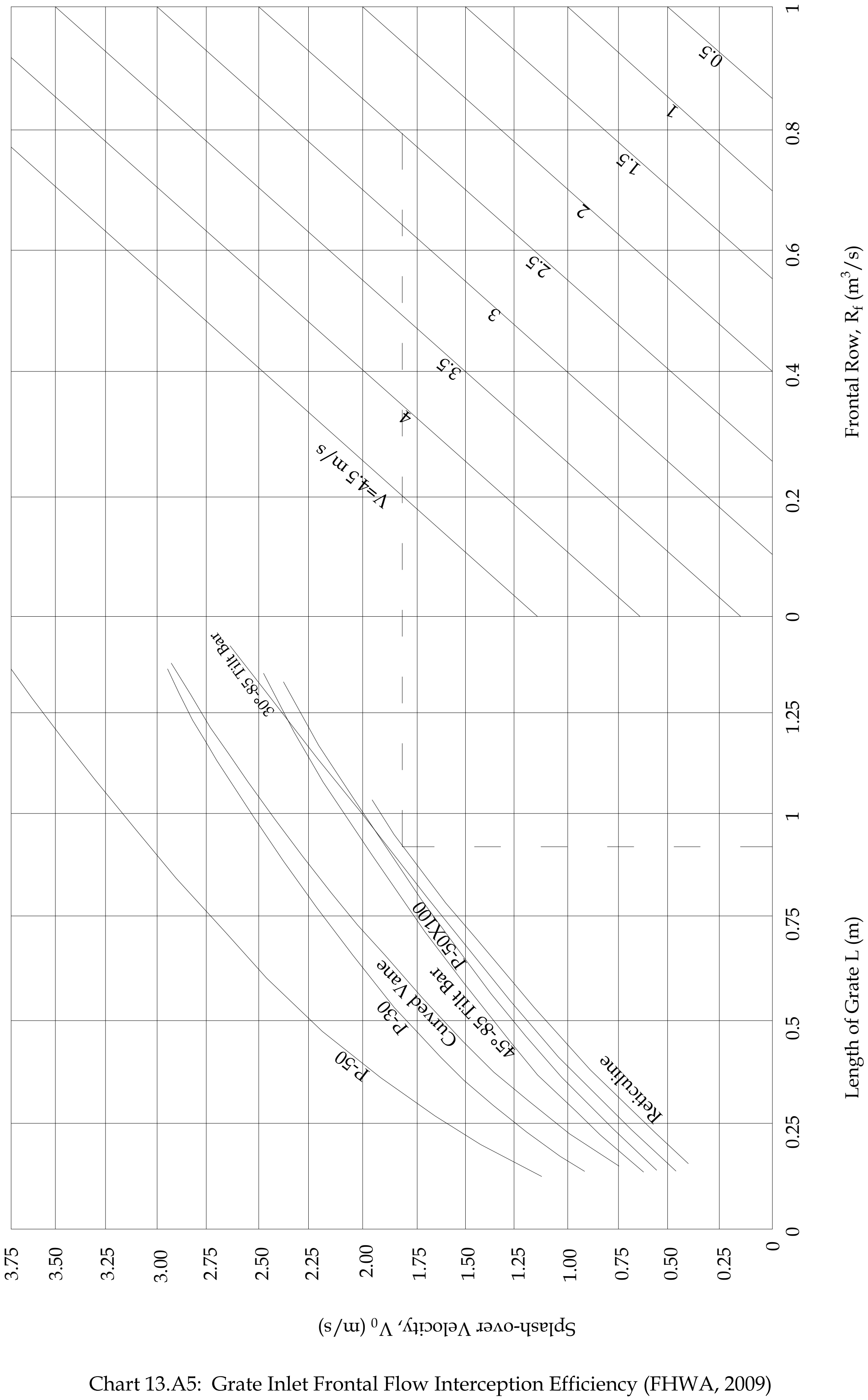


Chart 13.A5: Grate Inlet Frontal Flow Interception Efficiency (FHWA, 2009)

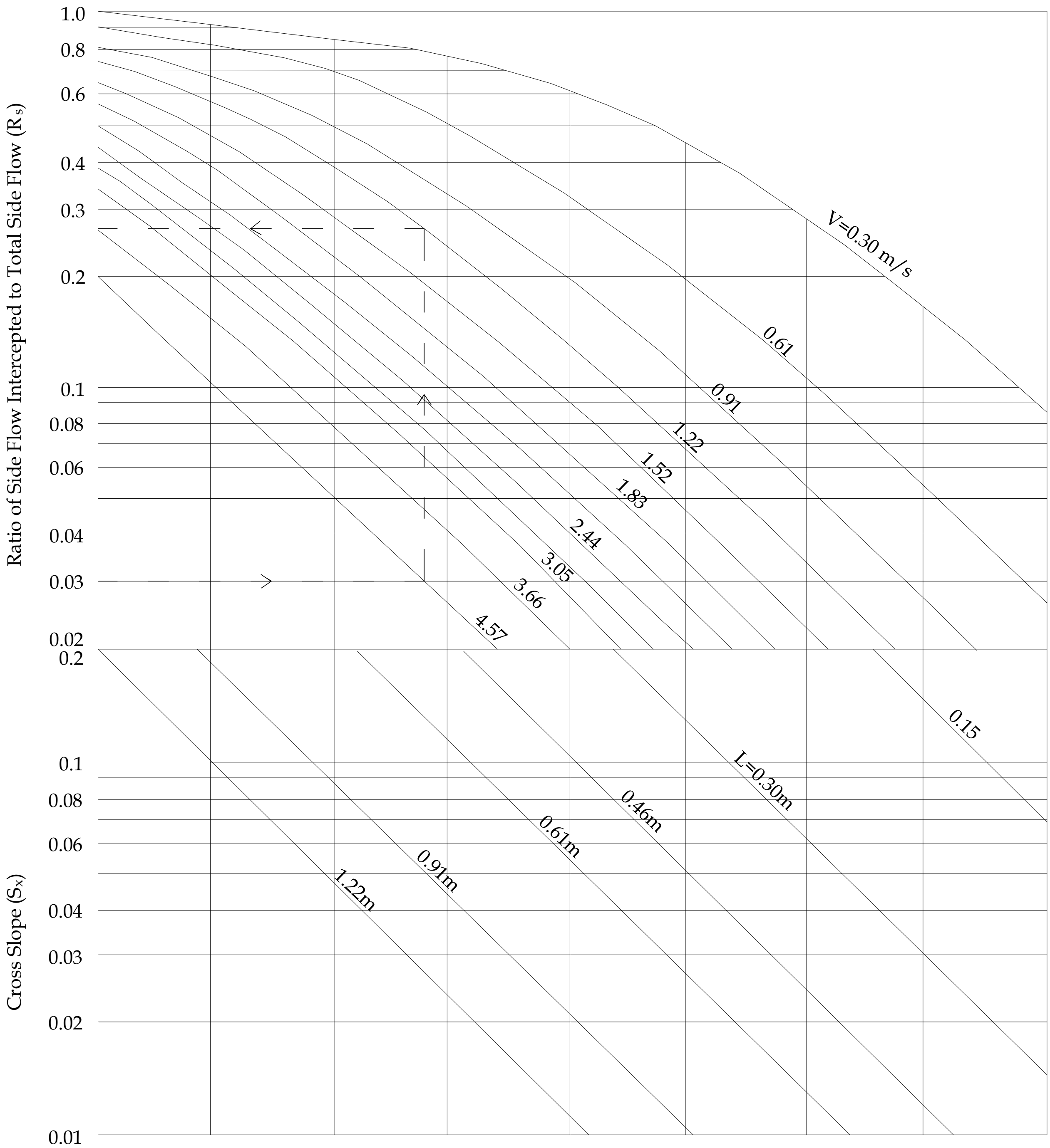


Chart 13.A6: Grate Inlet Side Flow Intercept Efficiency (FHWA, 2009)

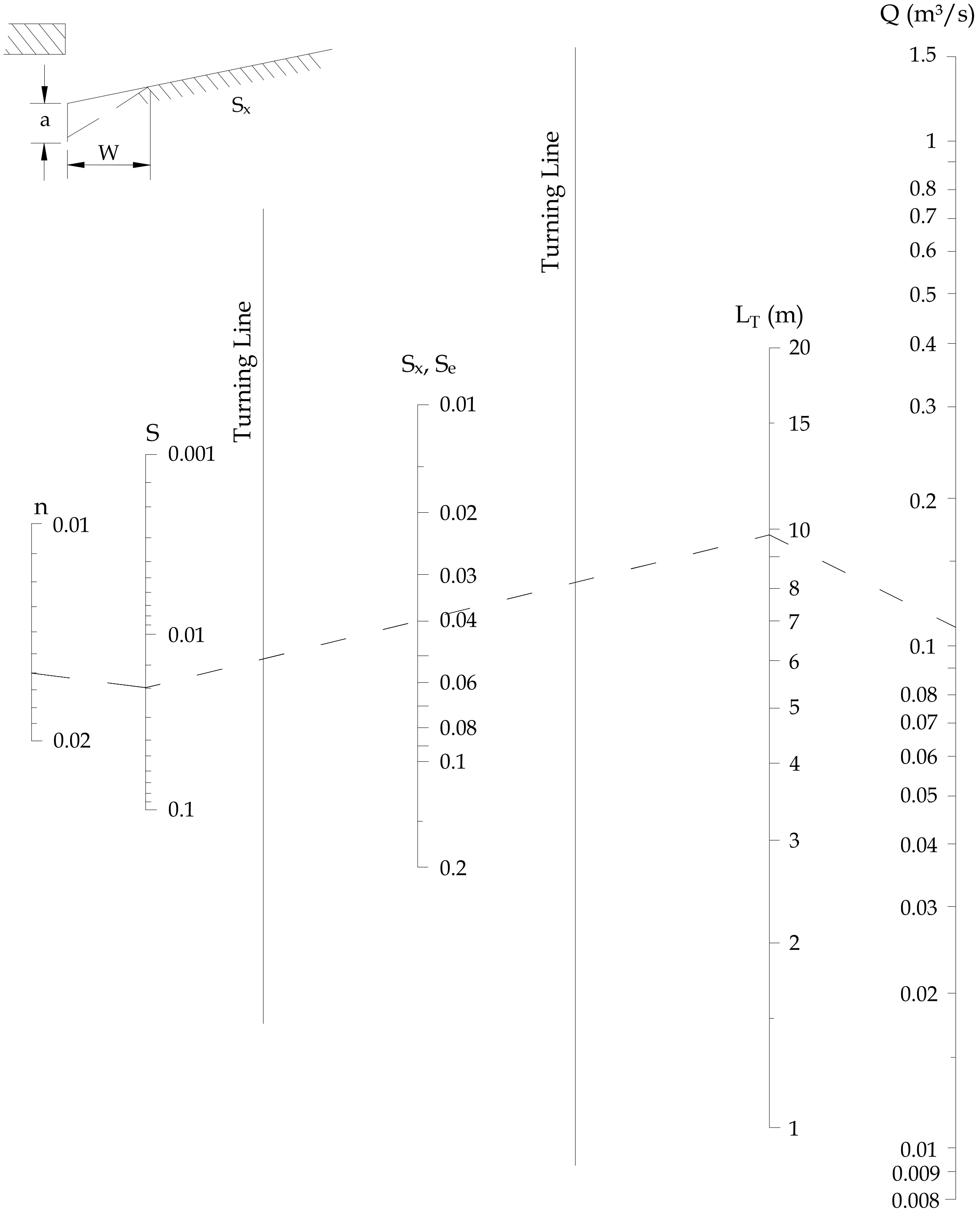


Chart 13.A7: Curb Opening and Slotted Drain Inlet Length for Total Interception (FHWA, 2009)

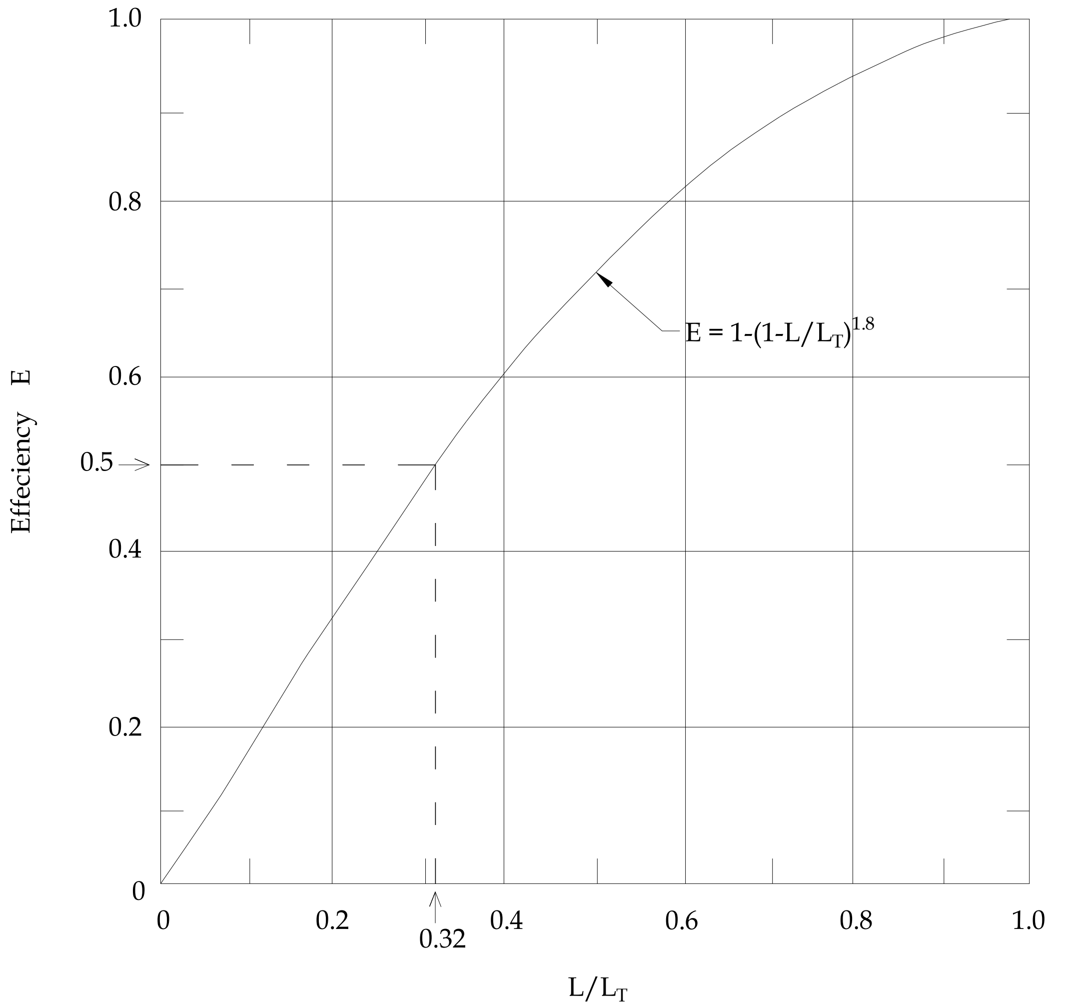


Chart 13.A8: Curb-Opening and Slotted Drain Inlet Interception Efficiency (FHWA, 2009)

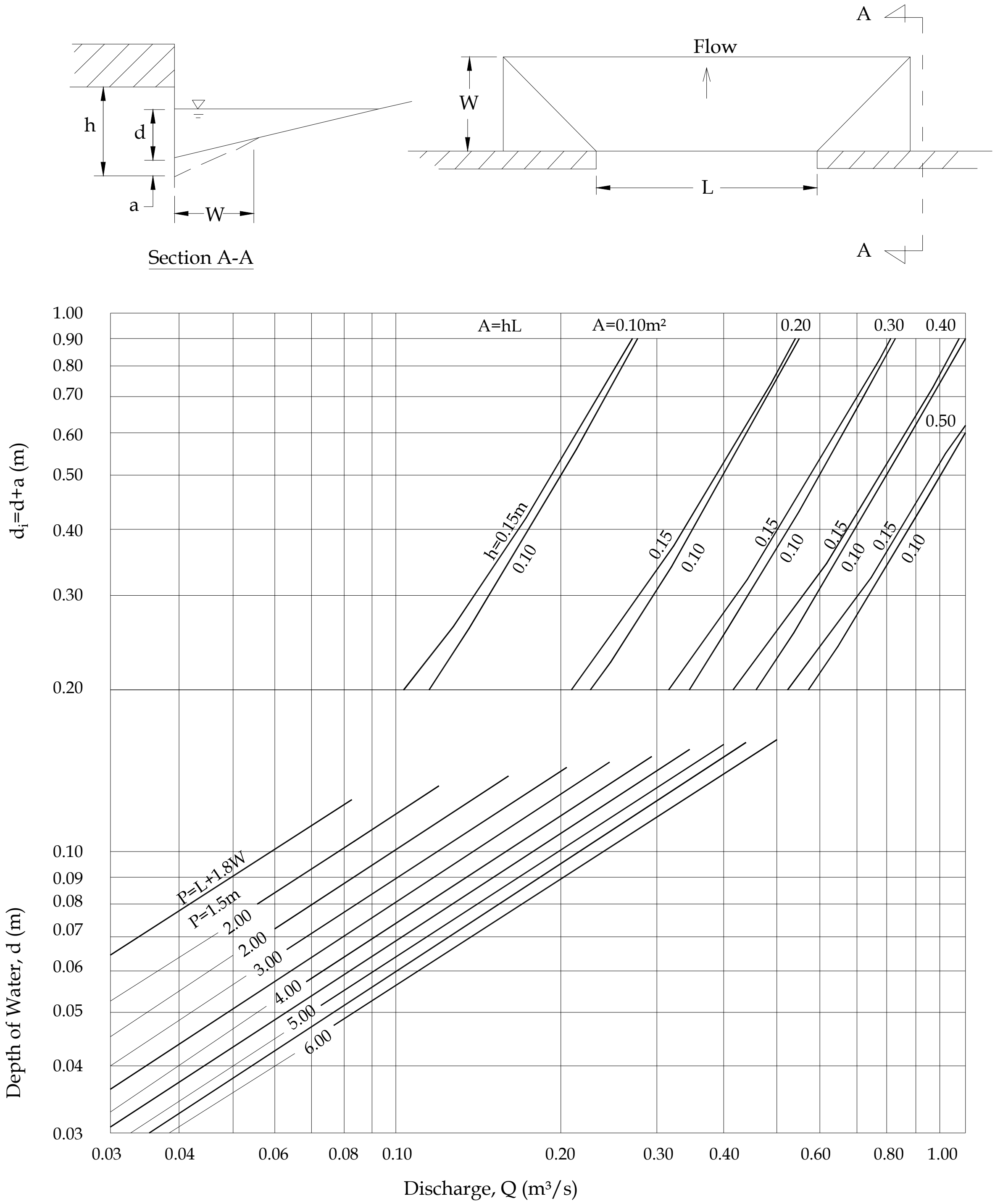


Chart 13.A9: Curb-Opening Inlet Capacity in Sump Location (FHWA, 2009)

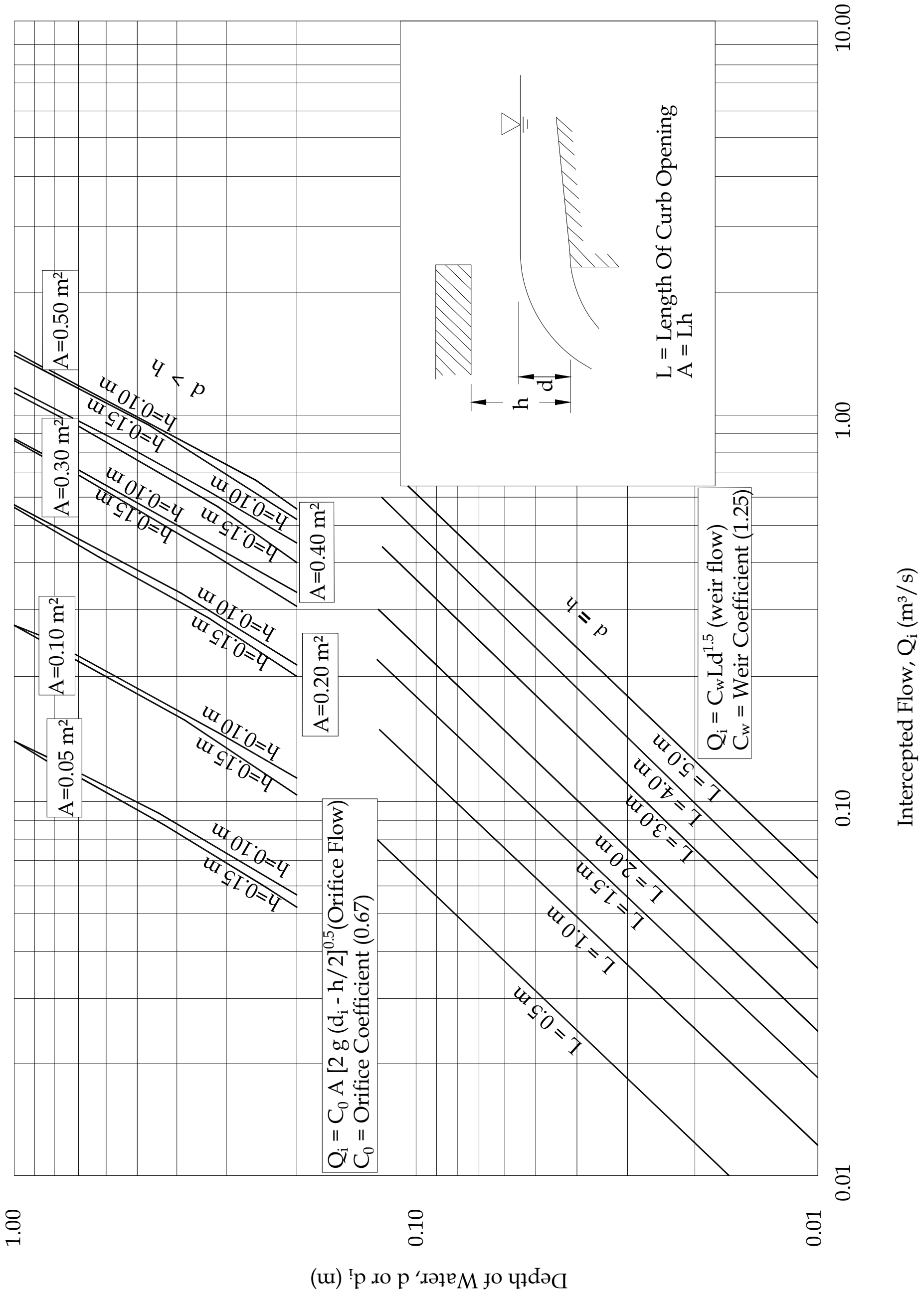


Chart 13.A10: Undepressed Curb-Opening Inlet Capacity in Sump Conditions (FHWA, 2009)

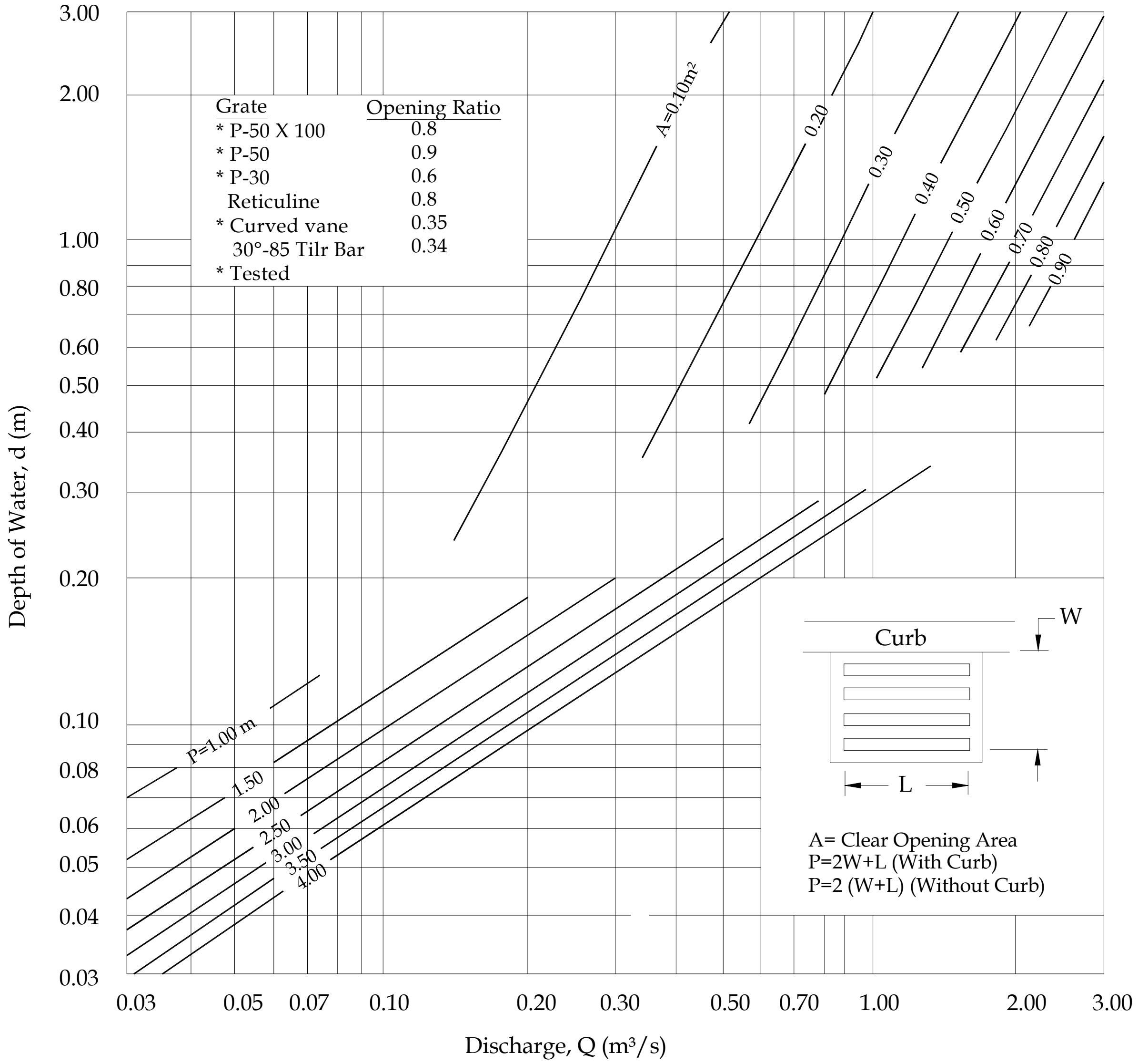
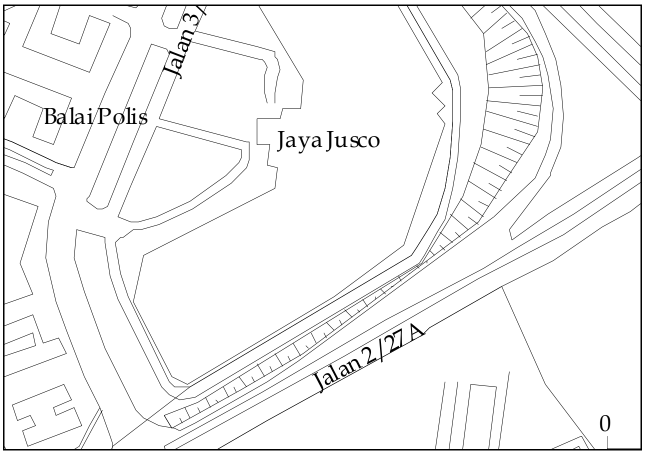


Chart 13.A11: Curb Opening Inlet Orifice Capacity (FHWA, 2009)

APPENDIX 13.B EXAMPLE – UNIFORM GUTTER

Problem:

A rough alphalt roadway (Manning n = 0.016) is to be designed with a cross slope of 0.02, a longitudinal slope of 0.03 and triangular gutter is to be used for pavement drainage. The proposed roadway site is located in Wangsa Maju, Kuala Lumpur. Determine the spread of water on the roadway if the roadway section considered consist of a 13m wide with a length of 100m.



Solution

Reference	Calculation		Output
	Step 1. Calculate velocity, V To determine shallow concentrated flow velocity, assume the spread of gutter, T is 1m $V = 1/n\ R^{2/3}S^{1/2}$ $R=A/P$		
	$R=[(0.5\text{x}1\text{x}0.02)/(0.02+(0.02^2+1^2)^{0.5})]$	=	0.0098m
	$V = (1/0.016)(0.0098)^{2/3}(0.03)^{1/2}$	=	0.496m/s
	Step 2. Calculate time of concentration, t_c. Time of concentration, t_c $= L / 60V$		
	$= 100/(60)(0.496)$	=	3.36 minutes (use 5 min. minimum)

Reference	Calculation		Output
	Step 3. Calculate rainfall intensity, I for 5 minutes duration and 10 ARI. Years		
Equation 2.2	$i = \dfrac{\lambda T^{\kappa}}{(d+\theta)^{\eta}}$		
Table 2.B1	λ = 63.24 K = 0.162 θ = 0.137 η = 0.856 d = 0.0833		
	= $(63.24)(10)^{0.162}/(0.0833 + 0.137)^{0.856}$	=	335.25mm/hr
	Step 4. Calculate area of the location Area = (100)(13)	=	$1300m^2$ 0.13ha
	Step 5. Calculate flow		
Table 2.5	During 10 year storm event. Runoff coefficient, C = 0.95		
Equation 2.3	Q = $CIA/360$ = (0.95)(335.25)(0.13)/360	=	$0.115m^3/s$
	Step 6. Calculate spread, T		
Equation 13.1	$T = \sqrt[2.67]{\dfrac{[Q \times n]}{KS_x^{1.67} S_L^{0.5}}}$ $= \sqrt[2.67]{\dfrac{0.115 \times 0.016}{(0.376)(0.02)^{1.67}(0.03)^{0.5}}}$	=	3.04m

APPENDIX 13.C EXAMPLE - COMPOSITE GUTTER

Problem:

Given gutter width, W = 0.6m, S_L = 0.03, S_X= 0.04, n = 0.016, gutter depression, a = 50mm. Then, find spread, T based on flow, Q from Example in Appendix 13.B.

Solution:

Reference	Calculation		Output
	Step 1. Calculate the cross slope of the depressed gutter, S_w		
	$S_W = \frac{a}{W} + S_X$		
	$= \frac{0.05}{0.6} + 0.04$	=	0.123
	Step 2. Calculate Q_W		
	Try Q_S = 0.033m³/s		
Equation13. 3(b)	$Q_W = Q - Q_S$		
	= 0.115 – 0.033	=	0.082m³/s
	Step 3. Determine W/T ratio :		
Equation 13.6	$E_o = Q_W / Q$		
	= 0.082/0.115	=	0.713
	S_W / S_X = 0.123 / 0.04	=	3.08
Chart 13.A2	With the value of E_o and S_W / S_X, use chart 13.A2 to get the value of W/T		
	W/T	=	0.30
	$T = W/0.30$		
	= 0.6/0.30	=	2.00m
	Step 4. T_s based on assumed Q_S		
	$T_s = T - W$		
	= 2.00 – 0.6	=	1.40m
	Step 5. Q_S for calculated T_S		
Equation 13.1	$Q_S n = K S_X^{1.67} S_L^{0.5} T^{2.67}$		
	$=(0.376)(0.04)^{1.67}(0.03)^{0.5}(1.40)^{2.67}$	=	0.00074m³/s
	Q_s = 0.00074/0.016	=	0.046m³/s
	Step 6. Compare assumed Q_s with calculated Q_s		
	assumed Q_s = 0.033m³/s < calculated Q_s = 0.046m³/s		
	Step 7. Try new assumed Q_S		
	Q_S = 0.022m³/s		
	Q_W = 0.115 – 0.022	=	0.093m³/s
	$E_o = Q_W/Q$ = 0.093/0.115	=	0.809

Reference	Calculation		Output
	S_W/S_X = 0.123/0.04	=	3.08
Chart 13.A2	W/T	=	0.36
	T = 0.6/0.36	=	1.67m
	T_s = 1.67 – 0.6	=	1.07m
Equation 13.1	$Q_{sn} = KS_X^{1.67}S_L^{0.5}T_s^{2.67}$		
	$= (0.376)(0.04)^{1.67}(0.03)^{0.5}(1.67)^{2.67}$	=	0.000352m^3/s
	Q_s = 0.000352/0.016	=	0.022m^3/s
	<u>Step 8.</u>		
	Assumed Q_s of 0.022m^3/s equals calculated Q_s		
	Therefore, T	=	1.67m

APPENDIX 13.D EXAMPLE - V–SHAPED ROADSIDE GUTTER

Problem:

Given S_L = 0.01, n = 0.016, S_{X1} = 0.25 (Refer to Figure 13.2), S_{X2} = 0.04, S_{X3} = 0.02, distance $\overline{BC}$ = 0.6m (Refer to Figure 13.2). Then, find spread at flow based on Example in Appendix 13.B.

Solution:

Reference	Calculation		Output
	Step 1. Calculate S_x		
Equation 13.4	$S_X = \frac{S_{X1} S_{X2}}{S_{X1} + S_{X2}}$		
	$S_X = \frac{(0.25)(0.04)}{0.25 + 0.04}$	=	0.0345
	Step 2. Calculate T_1		
Equation 13.1 or Chart 13.A1	$T_1 = \sqrt[2.67]{\frac{[Q \times n]}{KS_X^{1.67} S_L^{0.5}}}$		
	$T_1 = \sqrt[2.67]{\frac{0.115 \times 0.016}{(0.376)(0.0345)^{1.67}(0.01)^{0.5}}}$	=	2.65m
	Step 3. Calculate $\overline{AC}$		
	To determine if T_1 is within S_{X1} and S_{X2} , calculate depth at point B in the V-shaped gutter, knowing *BC* and S_{X2}. Then, knowing the depth at *B*, distance AB can be computed.		
	S_{X2} = $dB/\overline{BC}$		
	dB = $\overline{BC}\ S_{X2}$		
	= (0.6)(0.04)	=	0.024m
	$\overline{AB}$ = dB/S_{X1}		
	= (0.024) / 0.25	=	0.096m
	$\overline{AC}$ = $\overline{AB}$ + $\overline{BC}$		
	= 0.096 + 0.6	=	0.696m ~ 0.7m
	0.7m < T_1 therefore, spread falls outside V-shaped gutter section.		
	Step 4. Calculate spread T (Refer to Figure 13.2)		
	Assumed $\overline{BD}$ = 3m.		
	dC = $\overline{CD}\ S_{X3}$		
	= (3.0-0.6) x 0.02	=	0.048m
	$\overline{AB}$ = $\frac{0.048 + 0.024}{0.25}$	=	0.0288m
	T = $\overline{AB}$ + $\overline{BD}$		
	= 0.288 + 3	=	3.288m

Reference	Calculation	Output
	Step 5. Calculate T based on Equation 13.1	
	Develope a weighted slope for S_{X2} and S_{X3} based on assumed $\overline{BD}$ = 3m	
	$S_{X_2} = \dfrac{0.024 + 0.048}{3}$ =	0.024
Equation 13.4	$S_X = \dfrac{S_{X1} S_{X2}}{S_{X1} + S_{X2}}$	
	$= \dfrac{(0.25)(0.024)}{(0.25 + 0.024)}$ =	0.0219
Equation 13.1	$T = \sqrt[2.67]{\dfrac{[Q \times n]}{K S_X^{\ 1.67} S_L^{\ 0.5}}}$	
	$= \sqrt[2.67]{\dfrac{(0.115)(0.016)}{(0.376)(0.0219)^{1.67}(0.01)^{0.5}}}$ =	3.53m
	The spread T computed in step 5 in higher than T computed in step 4	
	Step 6	
	Assume $\overline{BD}$ = 3.24m	
	$dC = \overline{CD}\ S_{X3}$	
	= (3.24-0.6) x 0.02 =	0.0528
	$AB = \dfrac{0.0528 + 0.024}{0.25}$ =	0.3072
	T $= \overline{AB} + \overline{BD}$	
	= 0.3072 + 3.24 =	3.55m
	Step 7.	
	$S_X = \dfrac{S_{X1} S_{X2}}{S_{X1} + S_{X2}}$	
	$Sx = \dfrac{(0.25)(0.023)}{(0.25 + 0.023)}$ =	0.0216
Equation 13.1	$T = \sqrt[2.67]{\dfrac{[Q \times n]}{K S_X^{\ 1.67} S_L^{\ 0.5}}}$	
	$= \sqrt[2.67]{\dfrac{(0.115)(0.016)}{(0.376)(0.0216)^{1.67}(0.01)^{0.5}}}$ =	3.56m
	T= 3.56m close to T= 3.55m computed based on assumed $\overline{BD}$ of 3.24m	
	Therefore T is =	3.56m

APPENDIX 13.E EXAMPLE – CURB OPENING INLET

Problem:

Given a curb-opening inlet with the following characteristics, S_L= 0.03, S_X= 0.04, Q = 0.115m^3/s (from Example in Appendix 13.B) n = 0.016. Find
(i) Q_i for 3m curb-opening
(ii) Q_i for a depressed 3m curb opening inlet with a continuous curb section.
a = 25mm
W = 0.6m

Solution:

Reference	Calculation		Output
	Solution (i) :		
Equation 13.12 or Chart 13.A7	Step 1. Determine the length of curb opening required for total interception of gutter flow		
	L_T = $0.817\, Q^{0.42}\, S_L^{0.3}\, (1/(n.S_X))^{0.6}$		
	= $(0.817)(0.115)^{0.42}(0.03)^{0.3}[1/(0.016 \times 0.04)]^{0.6}$	=	9.49m
Equation 13.13 or Chart 13.A8	Step 2. Calculate the curb-opening efficiency.		
	L/L_t = 3/9.49	=	0.32
	E = $1 - (1 - L/L_t)^{1.8}$		
	= $1 - (1- 0.32)^{1.8}$	=	0.5
Equation 13.11	Step 3. Calculate the interception capacity.		
	Q_i = $E\,Q$		
	= (0.5)(0.115)	=	0.058m^3/s
	Solution (ii) :		
	Step 1. Determine W/T ratio.		
	Determine spread, T, (Procedure from Example 1 in Appendix 13.C		
Equation 13.3a or Chart 13.A2 and Equation 13.1 or Chart 13.A1	Assume Q_s = 0.036m^3/s		
	Q_W = $Q - Q_s$		
	= 0.115 – 0.036	=	0.079m^3/s
	E_o = Q_W/Q		
	= 0.079 / 0.115	=	0.687
	S_W = $S_X + a/W$		
	= (0.04) + (0.025/0.6)	=	0.082
	S_W/S_x = 0.082/0.04	=	2.05
Chart 13.A2	Determine W/T		
Equation 13.3a or	W/T = 0.32		
	T = 0.6 / 0.32	=	1. 88m
	T_s = $T - W$		
	= 1.88 – 0.6	=	1.28m

Reference	Calculation		Output
	<u>Calculate value of Q_s</u>		
Equation 13.1	$Q_s = \frac{K_u}{n} S_X^{1.67} S_L^{0.5} T^{2.67}$		
	$= \frac{0.376}{0.016}(0.04)^{1.67}(0.03)^{0.5}(1.28)^{2.67}$	=	$0.036 m^3/s$ (equals to Q_s assumed)
Equation 13.14	<u>Step 2. Determine efficiency of curb opening</u>		
	$S_e = S_X + S'_W E_o = S_x + (a/W)E_o$		
	$= 0.04 + (0.025/0.6)(0.079)$	=	0.0686
Equation 13.15 or Chart 13.7	$L_T = 0.817\ Q^{0.42}\ S_L^{0.3}\ (1/nS_X)^{0.6}$		
	$= (0.817)(0.115)^{0.42}\ (0.03)^{0.3}\ [1/(0.016 \times 0.0686)]^{0.6}$	=	6.86m
Equation 13.13 or Chart 13.A8	<u>Determine curb inlet efficiency.</u>		
	$L/L_T = 3/6.86 = 0.44$		
	$E = 1 - (1 - L/L_T)^{1.8}$		
	$= 1 - (1 - 0.44)^{1.8}$	=	0.65
Equation 13.11	<u>Step 3. Calculate curb opening inflow</u>		
	$Q_i = Q\ E = (0.115)(0.65)$	=	$0.075 m^3/s$

APPENDIX 13.F EXAMPLE –INLET SPACING

Problem:

Given the storm drainage system illustrated in Figure 13.F1 has the roadway characteristics which are n = 0.016, Pavement cross slope = 0.02, S_L = 0.03, allowable spread = 2.0m, gutter and shoulder cross slope, Sx = 0.04, and curb height = 0.3m. Then, find the design inlet spacing for a 0.60m wide by 0.9m long P50 x 100 grate, during a 10 years storm event.

Solution:

Reference	Calculation	Output
Figure 13.8	Steps 1-4 The calculation can begin at the the inlet located at station 21+00 (First inlet from the crest of the roadway. The crest which is the top of the drainage basin is located at station 22+00). The initial drainage area for locating the first inlet consist of a 13m wide roadway section with a length of 100m.	
	Step 5 Column 1 Inlet 1 Column 2 Station 21+00 Column 19 Gutter with a curb height =	0.3m
	Step 6 Column 3 Distance from top of drainage area to first inlet = 22+00– 21+00 = Width = 13m Drainage area = (100)(13) =	100m 1300m^2 0.13ha
Table 2.5	Step 7 Column 4 Runoff coefficient, C = 0.95	
	Step 8 Column 5 Firstly calculates velocity of gutter flow, assumed the spread of gutter, T is 1 m $V = 1/n\ R^{2/3}S^{1/2}$ $V = (1/0.016)(0.0192)^{2/3}(0.03)^{1/2}$ =	0.776m/s
Table 2.1	Calculate the time of concentration, t_c $t_c = L / (60\ V) = 100 / [(60)(0.776)]$ =	2.15 minutes (Use 5min. minimum)
Equation 2.2	Step 9 Column 6 Determine rainfall intensity, I for Wilayah Persekutuan Kuala Lumpur t_c = 5 minutes Find $^{10}I_5$ $i = \dfrac{\lambda T^{\kappa}}{(d+\theta)^{\eta}}$ $= (63.24)(10)^{0.162}/(0.0833 + 0.137)^{0.856}$ =	335.25mm/hr

Reference	Calculation	Output
Equation 2.3	Step 10. Column 7 Determine Gutter flow rate, Q $Q = CiA/360 = (0.95)(335.25)(0.13)/360$	= 0.115m³/s
	Step 11 Column 8 S_L	= 0.03
	Step 12 Column 9 S_x	= 0.04
	Step 13 Column 13 W	= 0.60m
Equation 13.1 or Chart 13.A1	Step 14 Column 14 Determine spread, T $T = \sqrt[2.67]{\frac{[Q \times n]}{KS_x^{1.67} S_L^{0.5}}}$ $= \sqrt[2.67]{\frac{(0.115)(0.016)}{(0.376)(0.04)^{1.67}(0.03)^{0.5}}}$ = 1.969 *m* (Less than allowable is 2 m, so proceed Next step.)	
Equation 13.2	Column 12 Determine depth at curb, d, using $d = TS_x = (1.969)(0.04)$	= 0.079m
	Step 15 Column 15 $W/T = 0.60/1.969$	= 0.305
	Step 16 Column 16 Select P50 x 100 grate measuring 0.60m wide by 0.9m long.	
Equation 13.6	Step 17 Column 17 Calculate intercepted flow, Q_t $E_o = 1-(1-W/T)^{2.67}$ $= 1 - (1-0.305)^{2.67}$	= 0.621
Equation 13.5	Calculate velocity, V $V = 0.752/n\ S_L^{0.5}\ S_x^{0.67}\ T^{0.67}$ $V = (0.752/0.016)(0.03)^{0.5}(0.04)^{0.67}(1.969)^{0.67}$	= 1.489m/s
Chart 13.A5	Find R_f $R_f = 1.0$	
Equation 13.9	Find R_s $R_s = 1/(1+ K_u\ V^{1.8} / (S_x\ L^{2.3}))$ $= 1 / (1+0.0828\ V^{1.8} / (S_x\ L^{2.3}))$ $= 1 / 1 +((0.0828)(1.489)^{1.8} / (0.04)(0.9)^{2.3})$	= 0.156
	Calculate value Q_t by using $Q_t = Q[R_f\ E_o + R_s\ (1-E_o)]$ $= 0.115[(1.0)(0.621) + 0.156\ (1-0.621)]$	= 0.0782m³/s
Equation 13.11	Step 18 Column 18 $Q_b = Q - Q_t$ $= 0.115 - 0.0782$	= 0.0368m³/s
	Step 19 Column 1 Inlet 2 Column 2 Station 20+ 32 (taking distance to successive inlets =68m Column 3 Drainage area = 68x13 Column 4 Runoff coefficient, C = 0.95	= 884m² 0.0884ha
	Step 20 Column 5 V = 0.776m/s (same as step 8 Col.5) $T_c = L/[60V] = (68)/(60)(0.776)$	= 1.46min (use 5min minimum)
Table 2.1 Equation 2.3	Step 21 Column 6 I = 335.21mm/hr (same as step 10) Step 22 Column 7 $Q = CiA/360 =(0.95)(335.25)(0.0884)/360$	= 0.0782m³/s

Reference	Calculation		Output
	Step 23 Column 11 = Col. 18 + Col. 7 = 0.0368 + 0.0782	=	$0.115 m^3/s$
	Step 24 Column14 T = 1.969m $T < T$ allowable = 2m Column 12 d = *(1.969)(0.04)*	=	0.079 < d curb = 0.3m
	Step 25 Column 16 Select P50 x 100 grate 0.60m wide by 0.9m long.		
	Step 26 Column 17 Q_t = $0.0782 m^3/s$		
	Step 27 Column 18 $Q_b = Q - Q_t$ = Column 11 – Column 17 = 0.115 – 0.0782	=	$0.0368 m^3/s$
	Step 28 Repeat steps 19 through 28 for each subsequent inlet down to the low point. This will end up with maximum distance to successive inlets of about 68m.		
	The required spacing of successive inlets is therefore 68m.		

Table 13.F1 Inlet Spacing Computation Sheet

INLET SPACING COMPUTATION SHEET

Date : JUN 2010 Route/Location : Wilayah Persekutuan Kuala Lumpur
Computed By: Ramli Sheet 1 of 1

Inlet		Gutter Discharge Design Frequency					Gutter Discharge Allowable Spread								Inlet Discharge			
No. (1)	Station (2)	Drainage Area(ha)(3)	Runoff Coefficient, C (4)	Time of Concentration, t_c (min) (5)	Rainfall Intensity, *i* (mm/hr) (6)	$Q = CIA/K_c$ (m^3/s) (7)	Longitudinal Slope, S_L (m/m) (8)	Cross Slope, S_x or S_w (m/m) (9)	Previous By-pass Flow (m^3/s)(10)	Total Gutter Flow (m^3/s)(11)	Depth, d (m) (12)	Grate or Gutter Width, W (m) (13)	Spread, T (m)(14)	W/T (15)	Inlet Type (16)	Intercept Flow, Q_i (m^3/s)(17)	By-pass Flow, Q_b (m^3/s) (18)	Remarks (19)
1	21+00	0.1300	0.95	5.00	335.25	0.1150	0.03	0.04	0.000	0.115	0.079	0.60	1.969	0.30	P50X100	0.078	0.037	0.3 (curb height)
2	20+32	0.0884	0.95	5.00	335.25	0.0782	0.03	0.04	0.037	0.115	0.079	0.60	1.969	0.30	P50X100	0.078	0.037	0.3 (curb height)

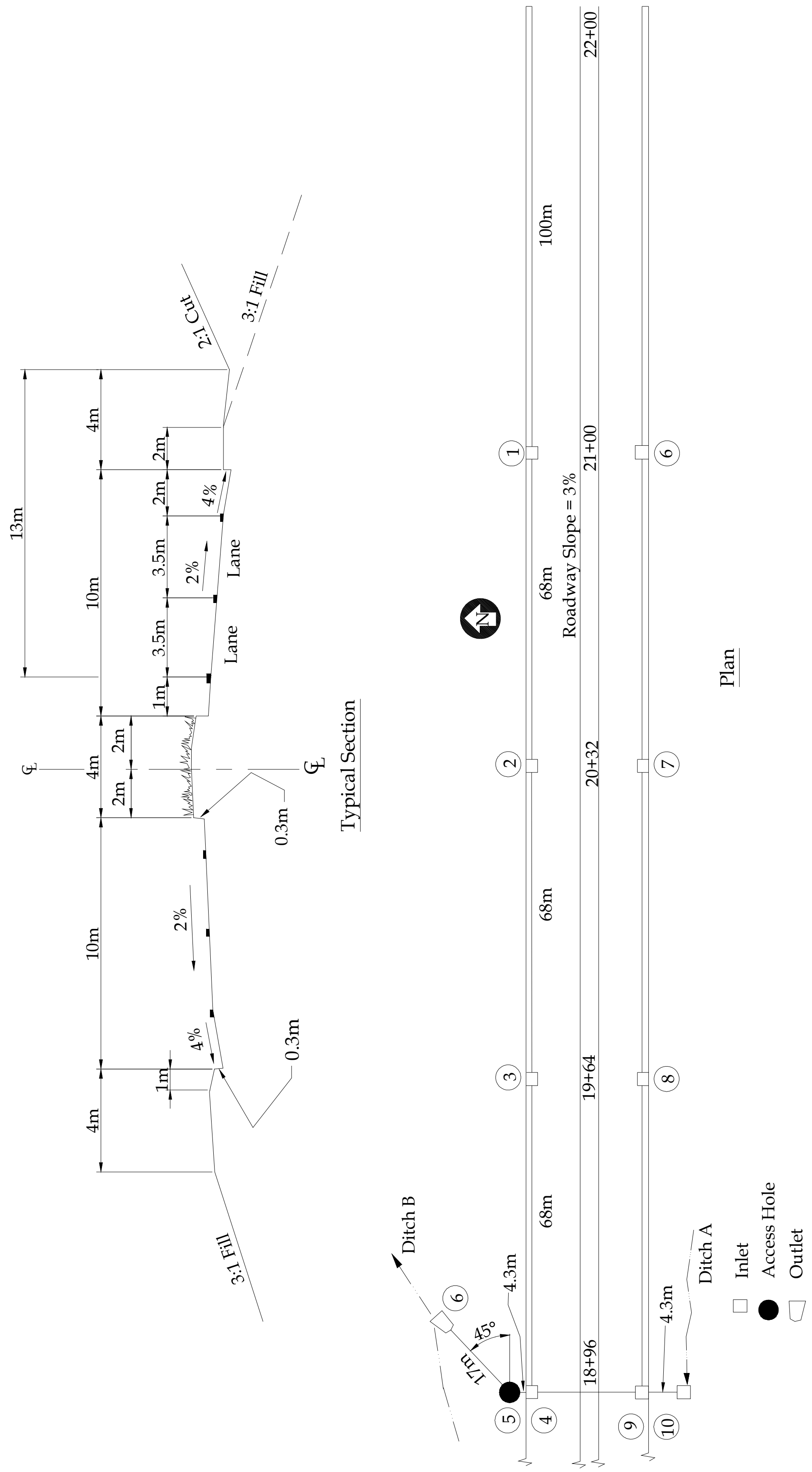


Figure 13.F1: Storm Drainage System for Example in Appendix 13.F

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