NASHVILLE STORMWATER MANAGEMENT MANUAL

VOLUME 3—THEORY

CHAPTER 4
Gutter and Inlet Hydraulics

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Chapter 4
GUTTER AND INLET HYDRAULICS

SYNOPSIS

Variables of major concern for pavement drainage evaluations include depth of gutter flow and pavement spread. These variables and roadway features such as cross slope, grade, and gutter sections can affect the size, type, and spacing of inlets. This chapter provides fundamentals of gutter flow and inlet interception capacity. Basic terminology is defined and the fundamentals for computing the capacity of curb-opening, gutter, slotted pipe, and combination inlets are presented for continuous grade and sump location conditions. The primary reference for information presented is HEC-12 (USDOT, FHWA, 1984).

4.1 FLOW

4.1.1 TYPICAL SECTIONS

A pavement gutter is the section of a roadway normally located at its outer edge to convey stormwater runoff. It may include a portion of a travel lane or be a separate section, but it usually has a triangular shape defined by the cross slope and curb.

A typical gutter section includes the following major components:

1. Pavement cross slope, S_x
2. Grade, S
3. Width of flow or spread, T
4. Width of depressed gutter flow, W
5. Depth of gutter flow, d
6. Cross slope of depressed gutter, S_w

Sketches showing the relationship of these components for three typical gutter sections are presented in Figure 4-1. The first sketch shows a curb and gutter section with a straight cross slope; the second a v-shaped section without a curb; and the third a depressed curb and gutter section of width, W and cross slope, S_w.

Figure 4-1

4.1.2 MANNING'S EQUATION

Gutter flow is a form of open channel flow that can be analyzed using a modified form of Manning's Equation (see Chapter 3). The modification is necessary because gutter flow typically has a water surface width of more than 40 times the depth of flow. Under such conditions, the hydraulic radius does not properly describe the cross section of flow. To compute gutter flow, Manning's Equation is integrated for an increment of width across this section. The resulting equation is expressed as:

$$Q = \frac{0.56}{n} S_x^{5/3} S^{1/2} T^{8/3} \qquad (4\text{-}1)$$

where:

Q = Gutter flow rate, in cfs

n = Manning's roughness coefficient

S_x = Pavement cross slope, in feet/foot

S = Grade, in feet/foot

T = Width of flow or spread, in feet

Resistance of the curb face is neglected in Equation 4-1. In practice, this omission is valid if the cross slope is 10 percent or less.

Depth of gutter flow or pavement spread are parameters that must be evaluated to properly establish the size, type, bypass, and spacing of inlets. The depth of flow and pavement spread are related mathematically as:

$$d = TS_x \qquad (4\text{-}2)$$

where:

d = Depth of gutter flow, in feet

T = Width of spread, in feet

S_x = Pavement cross slope, in feet/foot

For conditions where the pavement cross slope is curved or parabolic instead of straight, a special adaptation of Equation 4-1 is required to evaluate gutter capacity.

The relative effects of spread, cross slope, and grade on the capacity of a gutter with a straight cross slope are presented in Figure 4-2. Each of the lines is based on the relationship between these variables, as expressed by Equation 4-1. The width of spread is shown to have the greatest impact on gutter capacity, followed by cross slope and, to an even lesser degree, by grade. For example, doubling the spread would increase gutter capacity by 6 times, while doubling cross slope or grade would result in increases of only about 3 and 1.4 times, respectively.

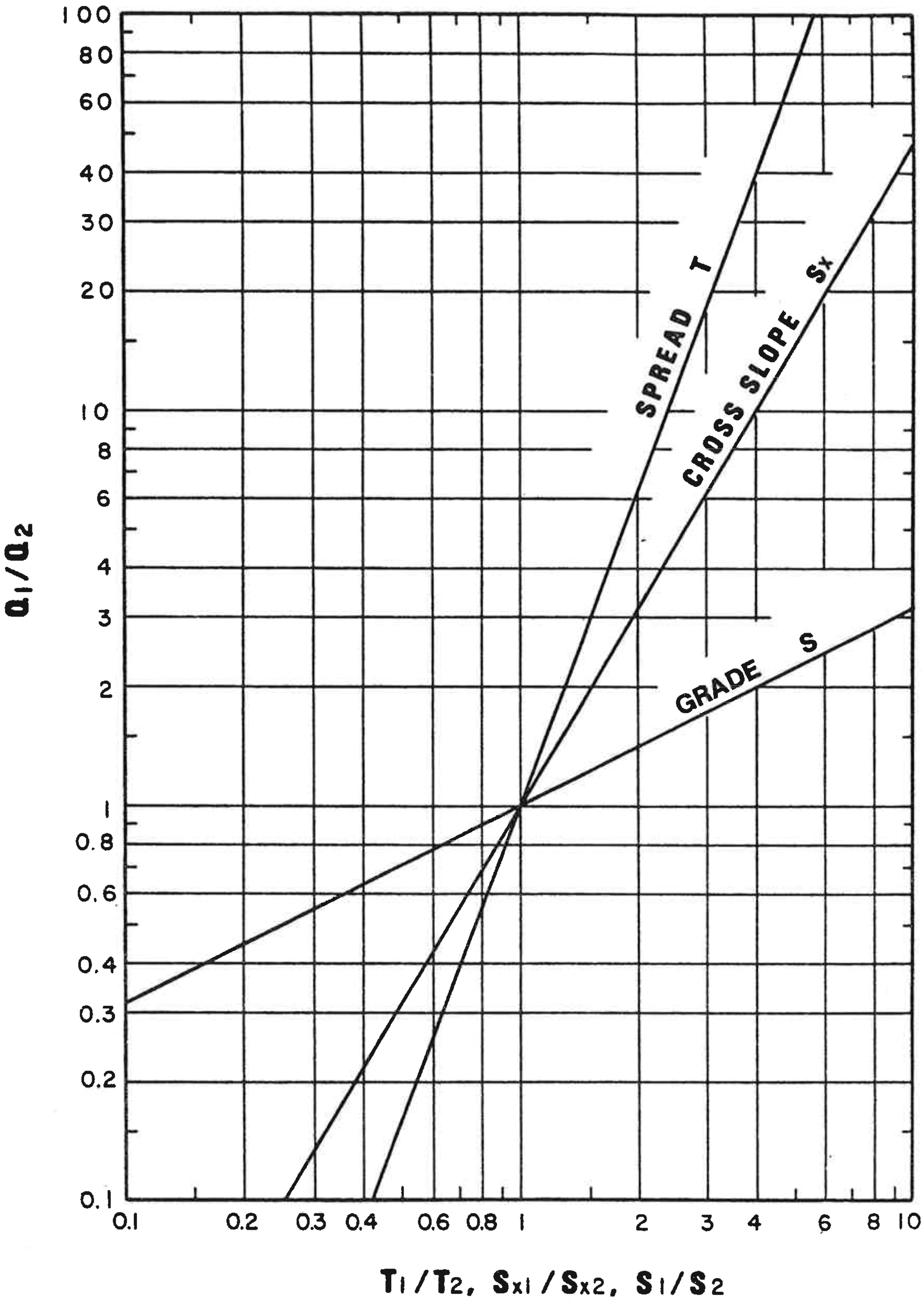
4.2 INLET TERMINOLOGY

Inlets for collecting pavement drainage can be divided into the following three major categories:

1. Curb-opening
2. Gutter
3. Combination

Curb-opening inlets are openings in the curb face that are generally placed in a depressed gutter section. Gutter inlets consist of a metal grate or grates placed over an opening in the gutter. A recent modification of the gutter inlet is a slotted pipe that allows pavement drainage to enter continuously along its longitudinal axis. Combination inlets are composed of both curb-opening and gutter inlets. Perspective drawings of inlet types are presented in Figures 4-3 and 4-4.

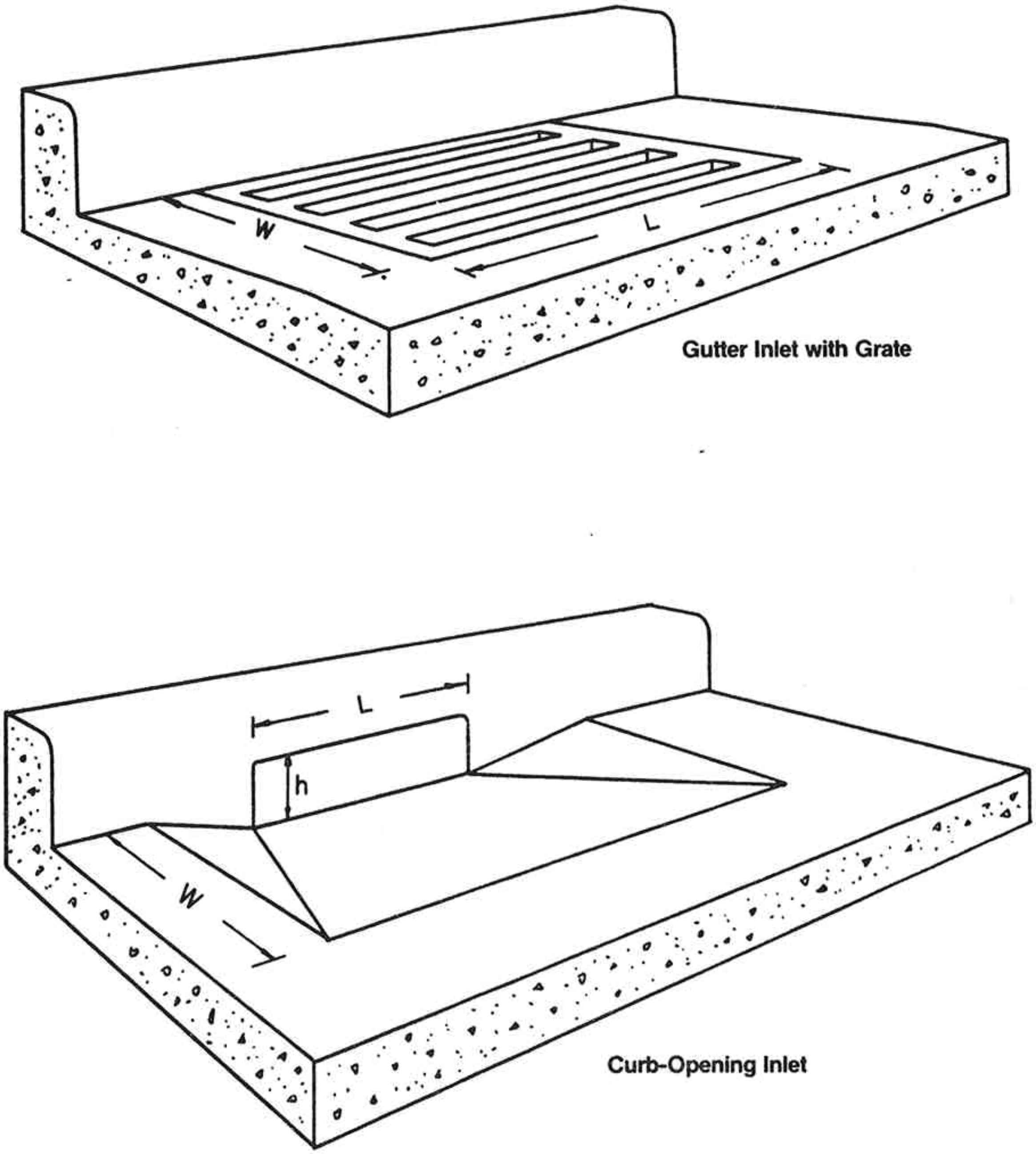
Pavement inlets can be placed either on a continuous grade or in a sump or sag condition. If pavement drainage is intended to enter the inlet from only one longitudinal direction, a continuous grade condition exists. On the other hand, if the inlet is located at a point where flow enters it from two directions, a sump condition exists.



NOTE: A straight cross slope is assumed and Equation 4-1 provides the basis for these relationships.

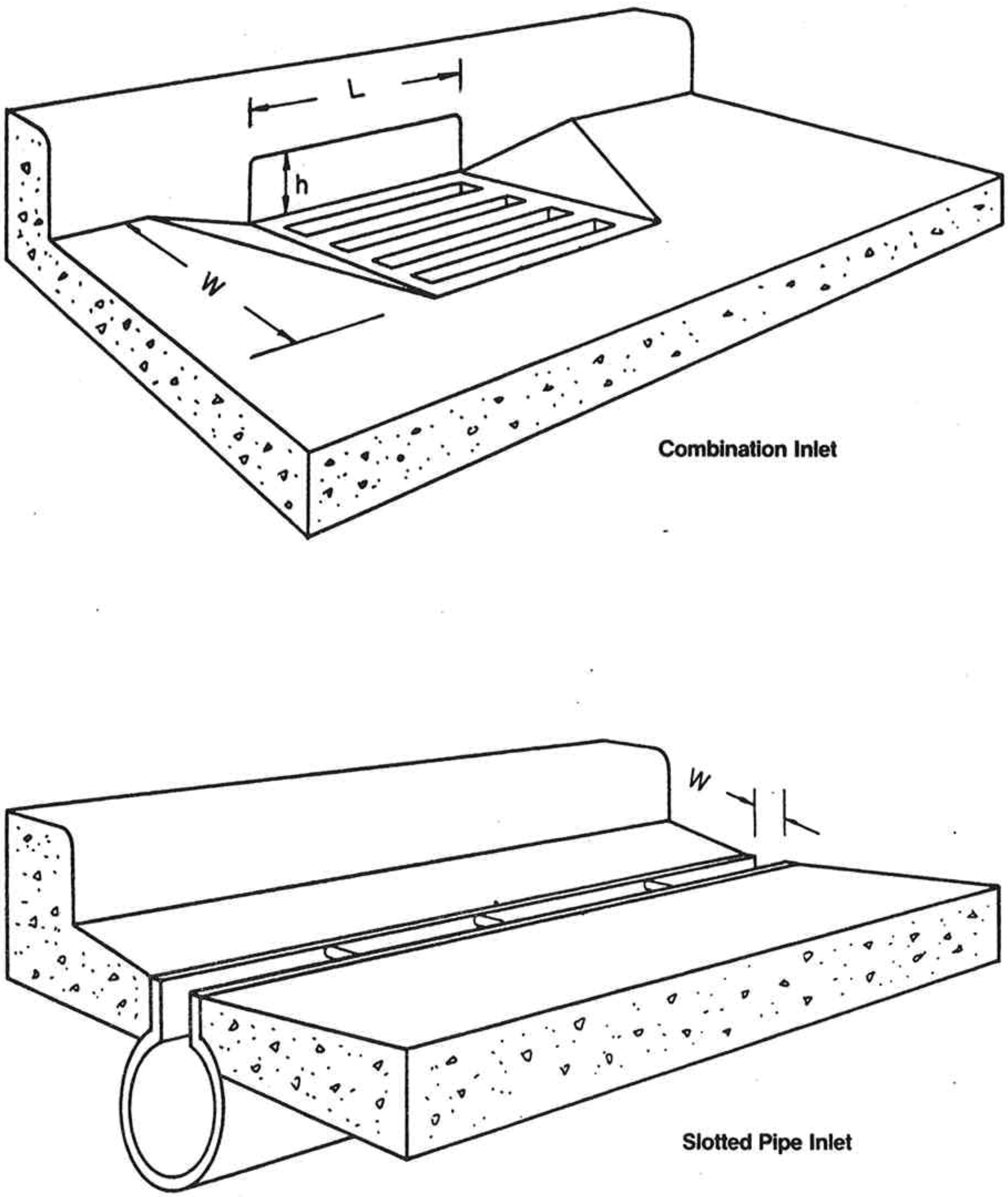
Reference: USDOT, FHWA, HEC-12 (1984).

FIGURE 4-2
Relative Effects of Spread, Cross Slope, and Grade on Gutter Flow Capacity



Reference: USDOT, FHWA, HEC-12 (1984).

FIGURE 4-3
Perspective Views of Gutter and Curb-Opening Inlets



Reference: USDOT, FHWA, HEC-12 (1984).

FIGURE 4-4
Perspective Views of Combination and Slotted Pipe Inlets

The interception capacity of an inlet is the gutter flow that enters an inlet under a given set of conditions. The capacity changes as those conditions change. Factors affecting the interception capacity of curb-opening and gutter inlets are briefly discussed in Sections 4.3 and 4.4.

The efficiency of an inlet is the percent of total gutter flow that the inlet will intercept for a given set of operating conditions. In mathematical form, efficiency is defined as:

$$E = \frac{Q_i}{Q}(100) \qquad (4\text{-}3)$$

where:

E = Efficiency of an inlet, in percent

Q_i = Intercepted flow, in cfs

Q = Total gutter flow, in cfs

Flow that is not intercepted by an inlet is called bypass, or carryover, and is expressed mathematically as:

$$Q_b = Q - Q_i \qquad (4\text{-}4)$$

where:

Q_b = Bypass flow, in cfs

Q = Total gutter flow, in cfs

Q_i = Intercepted flow, in cfs

In most cases, an increase in total gutter flow causes an increase in the interception capacity of an inlet and a decrease in its efficiency.

Pavement inlets do not provide an efficient method for collecting large quantities of stormwater. Therefore, non-pavement drainage should be collected upstream of the pavement when possible.

4.3 CURB-OPENING INLETS

The advantages of curb-opening inlets are that they are less susceptible to clogging and less hazardous to pedestrians and bicyclists than gutter inlets. However, they are not always as efficient.

4.3.1 CONTINUOUS GRADE

A curb-opening inlet located on a continuous grade functions as a falling head weir, the efficiency of which is affected by cross slope, grade, total gutter flow, and weir length. The interception capacity of the inlet depends primarily on the flow depth at the curb and the curb-opening geometry. For a given gutter flow, interception capacity and efficiency will be lost as the grade is increased, because depth at the curb decreases as velocity increases. If the curb opening can be depressed several inches below the gutter elevation, the interception capacity of the inlet can be increased. This can be done as part of a continuous gutter depression or as a local depression at the inlet. Interception capacity increases with higher gutter flows, but efficiency decreases.

The length of curb-opening inlet required for total interception of gutter flow on a pavement section with a straight cross slope can be computed using the equation:

$$L_T = 0.6\, Q^{0.42}\, S^{0.3} \left(\frac{1}{n\, S_x}\right)^{0.6} \qquad (4\text{-}5)$$

where:

L_T = Length required to intercept 100 percent of gutter flow on continuous grade, in feet

Q = Total gutter flow, in cfs

S = Grade of the gutter, in feet/foot

n = Manning's roughness factor

S_x = Cross slope of pavement, in feet/foot

The efficiency of curb-opening inlets shorter than the length required for total interception is computed using the equation:

$$E = 1 - (1 - L/T)^{1.8} \quad (4\text{-}6)$$

where:

E = Efficiency of the inlet on a continuous grade, expressed as a decimal

L = Length of curb opening, in feet

L_T = Length required to intercept 100 percent of gutter flow on continuous grade, in feet (see Equation 4-5)

The length of inlet required for total interception by depressed curb-opening inlets or curb openings in depressed gutter sections can be evaluated using Equation 4-5, once the equivalent cross slope is calculated using the equation:

$$S_e = S_x + S'_w E_o \quad (4\text{-}7)$$

where:

S_e = Equivalent cross slope, in feet/foot

S_x = Cross slope of pavement, in feet/foot

S'_w = Cross slope of the depressed gutter measured relative to the cross slope = a/12w, in feet/foot

a = Gutter depression, in inches

w = Width of depressed gutter, in feet

E_o = Ratio of the depressed section flow to the total gutter flow, expressed as a decimal (see Equation 4-13)

The equivalent cross slope, S_e, determined in Equation 4-7 replaces the cross slope, S_x, in Equation 4-5 to calculate the curb-opening length required to intercept 100 percent of gutter flow on continuous grades.

Top slab supports placed flush with the curb face can substantially reduce the interception capacity of curb openings. If intermediate top slab supports are required for structural support, they should be recessed several inches behind the curb face and rounded in shape.

4.3.2 SUMP LOCATIONS

Curb-opening inlets in sump locations operate as weirs up to a depth equal to the opening height. At depths above 1.4 times the opening height, the inlet operates as an orifice and, between these depths, a transition from weir to orifice flow occurs. The weir flow equation for a depressed curb-opening inlet is expressed as:

$$Q_i = 2.3\ (L + 1.8W)d^{1.5} \qquad (4\text{-}8)$$

where:

Q_i = Interception capacity of a depressed curb-opening inlet operating as a weir and located at a sump, in cfs

L = Length of curb opening, in feet

W = Lateral width of depression, in feet

d = Depth of gutter flow, based on width of spread and cross slope, in feet (see Equation 4-2)

Equation 4-8 is applicable for flow depths less than or equal to the curb-opening height plus the depth of the depression. This limitation is expressed mathematically as:

$$d \leq h + \frac{a}{12} \qquad (4\text{-}9)$$

where:

d = Depth at curb, measured from normal cross slope, in feet

h = Height of curb-opening inlet, in feet

a = Depth of depression, in inches

Since Equation 4-8 is based on a local depression, it will give conservative capacity estimates for inlets with a continuously depressed gutter.

The weir flow equation for curb-opening inlets without a depressed gutter is expressed as:

$$Q_i = 2.3 L d^{1.5} \tag{4-10}$$

where:

Q_i = Interception capacity of a non-depressed curb-opening inlet operating as a weir and located at a sump, in cfs

L = Length of curb opening, in feet

d = Depth of gutter flow, based on width of spread and cross slope, in feet (see Equation 4-2)

The depth limitation for weir flow represented by Equation 4-10 is expressed as:

$$d \leq h \tag{4-11}$$

where:

d = Depth of gutter flow, based on width of spread and cross slope, in feet (see Equation 4-2)

h = Height of curb opening, in feet

The orifice flow equation for evaluating the capacity of a submerged curb-opening inlet is expressed as:

$$Q_i = 0.67\ h\ L\ (2g\ d_o)^{0.5} \qquad (4\text{-}12)$$

where:

Q_i = Interception capacity of a curb-opening inlet operating as an orifice and located at a sump, in cfs

h = Height of curb opening, including the depression height, a, if appropriate, in feet

L = Length of curb opening, in feet

g = Acceleration due to gravity, 32.2 feet/second²

d_o = Effective head on the center of the orifice throat, in feet (see Figure 4-5)

for horizontal throat:

$$d_o = d_i - h/2$$

for inclined throat:

$$d_o = d_i - (h/2)\sin\Theta$$

for vertical throat:

$$d_o = d_i$$

d_i = Depth at lip of curb opening, in feet

As identified above, the effective head on the center of the orifice throat is dependent on the geometry of the inlet. Horizontal, inclined, and vertical throat curb-opening inlet geometries are illustrated in Figure 4-5, along with details for determining the effective depth. Equation 4-12 is applicable to depressed and undepressed curb-opening inlets, and the height of the curb opening includes the depression height, if appropriate.

$$Q = 0.87\, hL\sqrt{2gd_o}$$

L = LENGTH OF OPENING

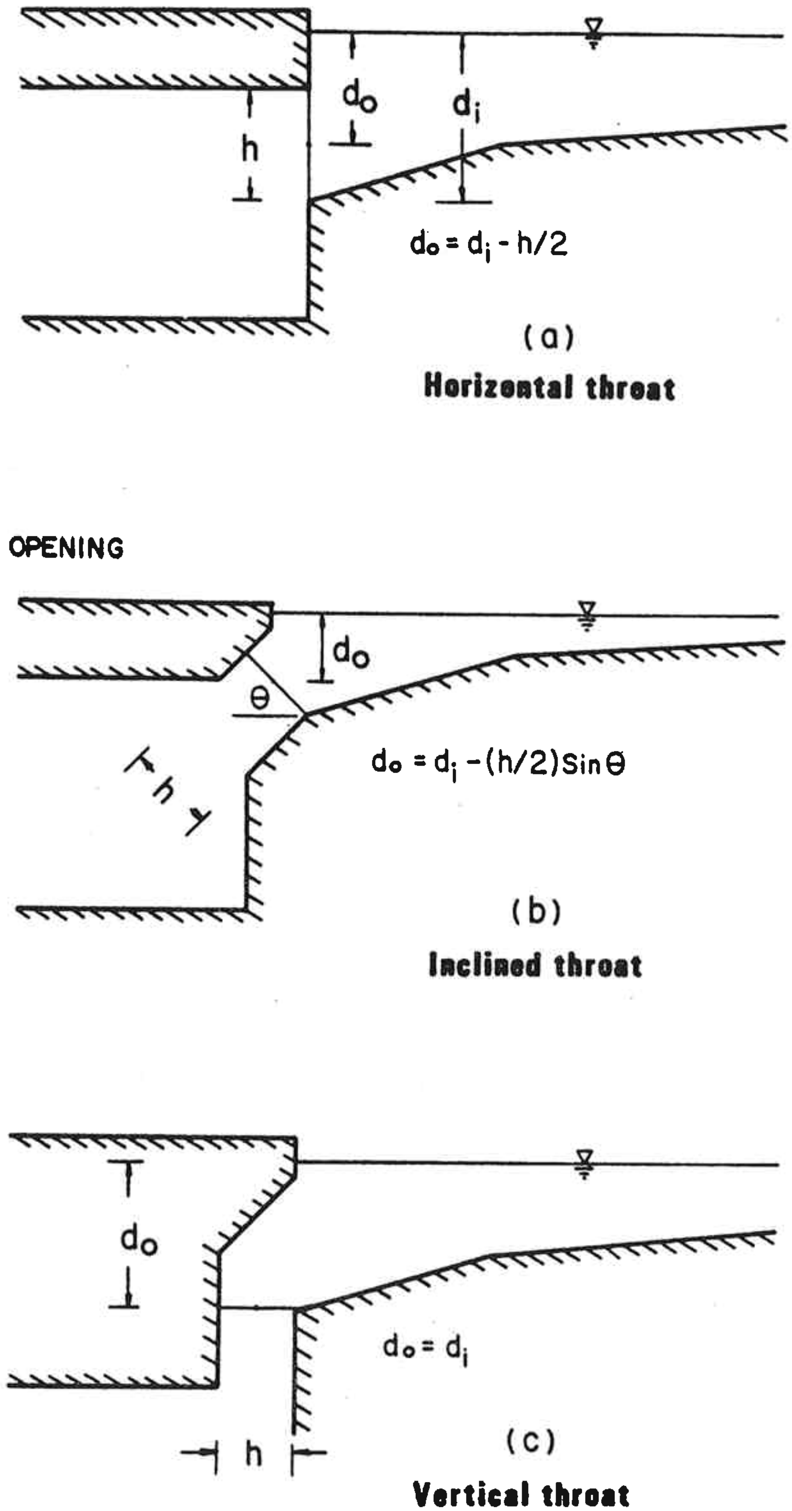


FIGURE 4-5
Effective Head for Horizontal, Inclined, and Vertical Throat Curb-Opening Inlets

4.4 GUTTER INLETS

Gutter inlets usually have one or more metal grates covering an opening in the gutter. Such inlets may not operate effectively where a potential exists for clogging from stormwater-carried debris.

4.4.1 CONTINUOUS GRADE

The water flowing in the section of a gutter inlet occupied by the grate is called frontal flow. When the gutter flow velocity is low enough, the grate inlet intercepts all of the frontal flow and a small portion of the side flow, which occurs along the length of the grate. As the gutter flow velocity increases, water may begin to skip, or splash over, the grate and the efficiency of the inlet may be reduced. If splashover does not occur, the capacity and efficiency of a gutter inlet will increase with an increase of the grade (the reverse of the effect on curb-opening and slotted inlets). This is because frontal flow increases with increased grade and all frontal flow will be intercepted if splashover does not occur.

The ratio of frontal flow to total gutter flow for a straight cross slope (see Figure 4-1) is expressed as:

$$E_o = \frac{Q_w}{Q} = 1 - (1 - W/T)^{2.67} \qquad (4\text{-}13)$$

where:

E_o = Ratio of frontal flow to total gutter flow

Q_w = Frontal flow in width, W, in cfs

Q = Total gutter flow, in cfs

W = Width of gutter inlet or grate (see Figure 4-3), in feet

T = Total spread of water in the gutter (see Figure 4-1), in feet

The ratio of side flow to total gutter flow is expressed as:

$$\frac{Q_s}{Q} = 1 - \frac{Q_w}{Q} = 1 - E_o \qquad (4\text{-}14)$$

where:

Q_s = Side flow intercepted by gutter inlet, in cfs

Q = Total gutter flow, in cfs

Q_w = Frontal flow in width, W, in cfs

E_o = Ratio of frontal flow to total gutter flow (see Equation 4-13)

The ratio of intercepted frontal flow to total frontal flow is expressed as:

$$R_f = 1 - 0.09\ (v - v_o) \qquad (4\text{-}15)$$

where:

R_f = Ratio of intercepted frontal flow to total frontal flow

v = Average velocity of gutter flow, in feet/second

v_o = Average gutter velocity where splashover first occurs, in feet/second

The ratio of intercepted side flow to total side flow is expressed as:

$$R_s = 1/\left[1 + \frac{0.15\ v^{1.8}}{S_x\ \ L^{2.3}}\right] \qquad (4\text{-}16)$$

where:

R_s = Ratio of intercepted side flow to total side flow

v = Average velocity of gutter flow, in feet/second

S_x = Cross slope of gutter, in feet/foot

L = Length of grate, in feet

The operating efficiency of a gutter inlet with a grate located on a continuous grade is expressed as:

$$E = R_f E_o + R_s (1 - E_o) \qquad (4\text{-}17)$$

where:

E = Efficiency of the gutter inlet on a continuous grade

R_f = Ratio of intercepted frontal flow to total frontal flow (see Equation 4-15)

E_o = Ratio of frontal flow to total gutter flow (see Equation 4-13)

R_s = Ratio of intercepted side flow to total side flow (see Equation 4-16)

The interception capacity of a gutter inlet with a grate located on a continuous grade is equal to the efficiency of the inlet multiplied by the total gutter flow, which can be expressed as:

$$Q_i = EQ = Q [R_f E_o + R_s (1 - E_o)] \qquad (4\text{-}18)$$

where:

Q_i = Interception capacity of the gutter inlet on a continuous grade, in cfs

E = Efficiency of the gutter inlet on a continuous grade (see Equation 4-17)

Q = Total gutter flow, in cfs

R_f = Ratio of intercepted frontal flow to total flow (see Equation 4-15)

E_o = Ratio of frontal flow to total gutter flow (see Equation 4-13)

R_s = Ratio of intercepted side flow to total side flow (see Equation 4-16)

4.4.2 SUMP LOCATIONS

Gutter inlets in sump locations operate as weirs up to depths that are dependent on grate size and configuration, and as orifices at greater depths. A transition occurs between weir and orifice flow depths. In this transition, the capacity is ill-defined and may fluctuate between weir and orifice control.

The efficiency of inlets in passing debris is critical in sump locations. If the inlet plugs, hazardous ponding conditions can result. Since gutter inlets with grates tend to clog, it is generally beneficial to place a curb-opening inlet behind each grate to intercept debris upstream of the gate. This is known as a combination inlet.

The interception capacity of a gutter inlet with a grate operating as a weir in a sump location is expressed as:

$$Q_i = 3.0 \; P \; d^{1.5} \qquad (4\text{-}19)$$

where:

Q_i = Interception capacity of a sump gutter inlet operating as a weir, in cfs

P = Perimeter of the grate, disregarding bars and the curb side, in feet

d = Depth of water above the top of the grate, in feet

The interception capacity of a gutter inlet with a grate operating as an orifice in a sump location is expressed as:

$$Q_i = 0.67\ A\ (2gd)^{0.5} \tag{4-20}$$

where:

- Q_i = Interception capacity of a sump gutter inlet operating as an orifice, in cfs
- A = Clear opening area of the grate, in square feet
- g = Acceleration due to gravity, 32.2 feet/second²
- d = Depth of water above the top of the grate, in feet

The transition zone from weir flow to orifice flow for gutter inlets in sump locations is typically between a depth of about 0.4 to 1.4 feet. However, this transition zone is known to vary depending on perimeter and clear opening area. The likely transition zone for a specific gutter inlet can be evaluated using interception capacity curves presented in Volume 2. These curves establish approximate limits of the transition zone based on experimental test results (USDOT, FHWA, HEC-12, 1984).

4.5 SLOTTED PIPE INLETS

Slotted pipe is a version of the gutter inlet that allows pavement drainage to enter the pipe continuously along its longitudinal axis. Slotted pipes can be used on curbed or uncurbed pavement and present minimal interference to traffic and pedestrians, but are susceptible to clogging.

4.5.1 CONTINUOUS GRADE

When placed on a continuous grade, slotted pipe inlets must be placed parallel to the direction of flow. If they are placed perpendicular to flow, splashover will occur and interception will be minimal. The interception capacity of slotted pipe inlets on a continuous grade has been found to be hydraulically similar to that of a curb-opening inlet.

Both inlets function as falling head weirs, with the flow subjected to lateral acceleration caused by the pavement cross slope.

The analysis of test data collected by the USDOT, FHWA (HEC-12, 1984) for slot widths greater than 1.75 inches indicates that the length of inlet required for complete interception of gutter flow can be computed using Equation 4-5, developed for curb-opening inlets.

The efficiency of a slotted pipe inlet on a continuous grade with a length shorter than that required for total interception can be computed using Equation 4-6, developed for curb-opening inlets.

4.5.2 SUMP LOCATIONS

Slotted pipe inlets at sump locations perform as weirs to depths of about 0.2 foot, depending on slot width and length. At depths greater than about 0.4 foot, they perform as orifices. A transition zone occurs between these two depths. The following equation can be used to estimate the capacity of a slotted pipe inlet operating as an orifice:

$$Q_i = 0.8 \, L \, W \, (2gd)^{0.5} \qquad (4\text{-}21)$$

where:

Q_i = Interception capacity of a slotted pipe inlet operating as an orifice, in cfs

L = Length of slotted pipe inlet, in feet

W = Width of slot, in feet

d = Depth of water at slot, in feet ($d \geq 0.4$ foot for orifice flow)

g = Acceleration due to gravity, 32.2 feet/second^2

For a slot width of 1.75 inches, Equation 4-21 becomes:

$$Q_i = 0.94\ L\ (d)^{0.5} \qquad (4\text{-}22)$$

For depths between 0.2 and 0.4 foot, the interception capacity of slotted pipe inlets can be computed with Equation 4-20; for depths less than 0.2 foot, Equation 4-19 is used.

4.6 COMBINATION INLETS

4.6.1 CONTINUOUS GRADE

On a continuous grade, the capacity of an unclogged combination inlet with the curb opening located next to the grate is approximately equal to the capacity of the grate inlet alone. A combination inlet with the curb opening located upstream of the grate has an interception capacity equal to the sum of the two inlets, except that the frontal flow of the grate is reduced by the amount of flow intercepted by the curb opening. By placing the curb opening upstream, debris is generally intercepted before it clogs the grate.

4.6.2 SUMP LOCATIONS

All debris carried by stormwater runoff that is not intercepted by upstream inlets will be concentrated at the inlet located at the low point or sump. Because this will increase the probability of clogging for grated inlets, it is generally appropriate to estimate the capacity of a combination inlet at a sump by neglecting the grate inlet capacity.