C5.8.4 Deck drains

C5.8.4.2 Edge drains

C5.8.4.2.1 Analysis and design

The following is the "Bridge Deck Drainage" document referred to in the manual [BDM 5.8.4.2.1].

Bridge Deck Drainage

Objectives:

- Control spread and depth of water to maintain tire traction.
- Provide drains that function properly with adequate maintenance.
- Preserve structural integrity and aesthetics of the bridge.

Background:

HEC-21 and HEC-22: These abbreviations refer to FHWA Hydraulic Engineering Circulars that are the basis for deck drain design [BDM 5.8.4.1.5].

Design criteria: The primary reason for a good bridge deck drainage design is to provide for safe passage of vehicles during the design storm event. As spread of water from the curb increases, the risks of traffic accidents and delays, and the nuisance and possible hazard to pedestrian traffic increases. 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. Factors which influence the depth of water on the pavement are the length of the flow path, surface texture, surface slope, and rainfall intensity. If sheet flow or spread is of sufficient depth, a tire can separate from the pavement surface. This is known as hydroplaning. As the depth of water increases, the potential for vehicular hydroplaning increases. If the spread of water encroaches onto the traffic lane, the traffic may slow and cause a disruption in flow. The use of drainage structures along the roadway to capture the flow of water will reduce the depth and spread of the water.

The Bridge Deck Drainage Design spreadsheet available in the Bureau in the LRFD Bridge Design Applications folder and on the Bridges and Structures Bureau web site calculates the spread of water based on the individual characteristics of the bridge. The depth and spread of water are interrelated, as depth is a function of the spread and cross slope. The spread of water is used as the limiting factor since it is an easier value to calculate and understand. The spread of water from the design storm is generally limited to the width of the shoulder, as flow in the traveled road would create traffic hazards. Where a shoulder is provided, water should be carried entirely on the shoulder except in the unusual cases where a part of the traffic lane can be used in addition to the shoulder.

The spreadsheet is intended for use with the Iowa DOT standard tube drain [BDM 5.8.4.2.1 and BSB SS 1059, 4380, and 4383-4385]. The spreadsheet can also be used for other curb opening drains providing initial parameters are changed. For drains with a different overall design, consult the manufacturer's information for additional information, as the efficiency of the drain will be required in the spreadsheet.

Rainfall design criteria for design and check storms are contained in Table 1 and are intended for use throughout the State of Iowa for bridge deck drain design. For a check storm (larger rainfall event) at least one width of traveled lane should still be accessible to traffic during the event. (This could be one-half lane on each side of the bridge, for a total of one lane width). The design criteria for deck drains give the maximum allowable encroachment or spread of water on the deck for a particular storm. A considerable amount of water will still be flowing off the end of the bridge, and end drains will be required.

Table 1. Bridge Deck Drain Rainfall Criteria

Criterion	Design Storm	Check Storm

Rainfall Intensity	8 in/hr(1)	9.6 in/hr
Time of Concentration	5 min.	5 min.
Duration	5 min.	5 min.
Frequency	10 yrs.	25 yrs.

Table note:

(1) Rainfall intensity for a 10 yr. frequency, 5-minute duration storm, varies throughout the state of Iowa. We are using an 8 in/hr rainfall intensity for bridge deck drains throughout the state of Iowa. This variable can be changed in the spreadsheet if determined to be necessary by the engineer. A table of rainfall intensities for the State of Iowa can be found in the Design Bureau's Design Manual [DB DM 4A-5, Table 2].

The design computations in the spreadsheet were established using the Federal Highway Administration's Hydraulic Engineering Circulars, HEC-21 and HEC-22 [BDM 5.8.4.1.5]. For more detailed information regarding these topics, refer to these manuals.

End Drains: Bridge deck drainage is often less efficient than roadway sections because cross slopes are flatter and drainage inlets or scuppers are less hydraulically efficient and more easily clogged by debris. Because of the difficulties in providing for and maintaining adequate deck drainage systems, gutter flow from the roadway should be intercepted before it reaches a bridge. (For similar reasons, zero gradients and sag vertical curves should be avoided on bridges.) Runoff from bridges should be collected immediately after it flows onto the subsequent roadway section where larger grates and inlet structures can be used. Bridge end drains are usually placed at the time the bridge approach is paved, so the need for them should be discussed with the Design Bureau. The drain located at the end of a bridge is generally designed to handle all of the flows coming from the bridge, under the assumption that all deck drains are clogged. It may be necessary to provide a temporary bridge end drain during the period of time between bridge construction and the bridge approach paving. This is extremely important when the fill material is very erosive. Chapter 7 in HEC-21 details bridge end drain design.

Debris: Problems with clogging are largely local since the amount of debris varies significantly from one area to another. Partial clogging of inlets on grade rarely causes major problems. Thus, localities need not make allowances for reduction in inlet interception capacity unless local experience indicates such an allowance is advisable. There is an input box in the spreadsheet to change this variable if deemed necessary. Unless there is a known problem with debris, such as in a heavily wooded area, this value should remain at 100%.

Snow and corrosives: Water may freeze or fall as snow, making roadways slick and plugging drains. Rain may also pick up corrosive contaminants, which if allowed to come into contact with structural members, may cause deterioration. Uncontrolled water can cause serious erosion of embankment slopes and even settlement of pavement slabs. The rain that falls on a structure may cause stains and discoloration on exposed faces if it is not collected and disposed of properly. Deck drains should prevent water, road salt, and other corrosives from contacting the structural components. The primary advantage of the standard tube drains is the removal of water from the bridge during lighter rains and for the removal of water from snowmelt. Proper designs and procedures can ensure that drains are working and bridge decks are free of standing water. Proper design provides benefits related to traffic safety, maintenance, structural integrity, and aesthetics.

Downspouts: Pipes hanging on a bridge lack aesthetic appeal, however pipes buried in concrete or concealed within a structure present maintenance challenges. A designer is cautioned against placing the drainage system within the superstructure. Drain pipes should not be installed through box girders. In most cases, the pipe leaks, freezes, and damages the box girder. Downspouts should, as a minimum, be 6 to 8 inches in diameter, with 8 inches preferred. For details which are more complex than a free fall situation, see pages 33-36 in HEC-21.

Design Steps: The design of the drainage system involves three basic steps. First, determine drain locations in accordance with location guidelines and restrictions [BDM 5.8.4.2.1]. Then, choose the type of drain. The choice of the type of drain will nearly always be the standard tube drain. If a different drain type is chosen, the dimensions and/or efficiency values of the drain will need to be changed in the spreadsheet. Finally, choose the spacing for the bridge deck drains. The next sections discuss the procedure in detail. The first section addresses the variables considered in design. The second section details the design procedure. The last section then addresses inlets with a sag condition.

In conclusion, effective bridge deck drainage is important for the following reasons: hydroplaning often occurs at shallower depths on bridges due to the reduced surface texture of concrete bridge decks, moisture on bridge decks freezes before surface roadways, and deck structural and reinforcing steel is susceptible to corrosion from deicing salts. Therefore, the engineer must develop solutions that control the spread of water into traffic lanes, control the depth of water available to reduce traction, do not interfere with the architectural beauty or structural integrity of the bridge, and function properly with adequate maintenance.

Hydraulic Analysis

All references and equations are from HEC-22 unless otherwise noted. Equation, chart, and page numbers are given in parentheses, i.e. (Eq. 4-2).

Definition of Variables:

Constants Used in Equations:

Rainfall Parameters (these values are typical and may be changed in special situations):

Run-off Coefficient, C = 0.9

Manning's Coefficient, n = 0.016

Rainfall Intensity, i = 8 in./hr.

Equation Constants:

K_m = 0.56 (Eq. 4-2)

K_v = 2*K_m = 1.12 (Eq. 4-13, Chart 4B)

K_f = 0.09 (Eq. 4-18)

K_s = 0.15 (Eq. 4-19)

Weir Coefficient, C_w = 3.0, for rectangular opening (Eq. 4-26)
= 2.3, for depressed curb (Eq. 4-28)
= 3.0, for non-depressed curb (Eq. 4-30)

Orifice Coefficient, C_O = 0.60, for circular opening (Pg. 8-21)
= 0.67, for rectangular (grate or curb) opening (Eq. 4-27)

Acceleration of Gravity, g = 32.2 ft/s^2

Area Constant (for unit conversion), $A_{constant}$ = 43,560

Values Specific to Project:

Width of Area Being Drained, W_p = typically width from crown to gutter [1]

Allowable Width of Spread, T_{all} = typically shoulder only [2]

Cross Slope, S_x = typically 2 % [3]

Longitudinal Slope, S_L = Profile Slope at location of drain [3]

Cross Slope at Intake, $S_w = S_x + a/W$ (to be conservative, a=0 and thus $S_w = S_x$)

Efficiency of drain due to debris, E_{deb} = typically 100 % [4]

1. W_p should include the entire area contributing to the drain, usually the width from the crown to the edge of the road. The width of sidewalks draining onto the deck should also be included. On superelevated decks, the entire deck width drains to one side; inlets are only needed on the low side of the bridge.

2. T_{all} is typically the width of the shoulder (from the edge of the traveled way to the edge of the road). See the Bridge Design Manual for more guidance and T_{all} values for various situations.

3. The spreadsheet will automatically calculate the S_L at the location of interest. If for some reason the user cannot calculate S_L, or if S_X varies over the area of interest, the smallest (and therefore most conservative) slope should be used. To avoid errors, slopes should be taken as no smaller than 0.3%.

4. In areas where debris and clogging will typically be a problem, this can be reduced to better reflect the efficiency of the inlet. A heavily wooded area is an example of where the efficiency may be reduced.

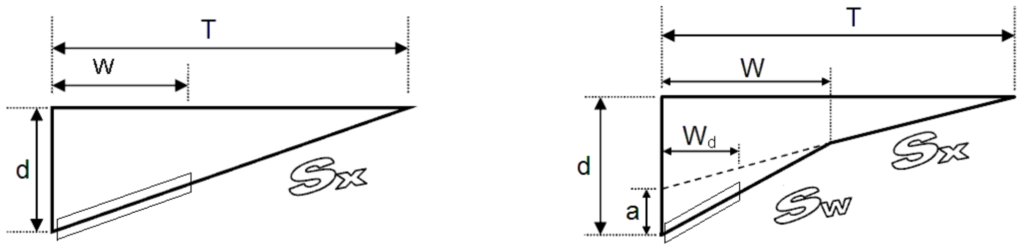


Figure 1: Gutter Cross Sections

Iowa DOT Drain Dimensions:

	Standard Tube Drain BSB SS 4380, 1059	Aesthetic Deck Drain BSB SS 1054
Length of Drain Opening, L	= 0.625 ft.	= 0.75 ft.
Width of Drain, W_d	= 0.2917 ft.	= 4.0 ft.
Depth of Gutter Depression, a	= 1.0 in.	= 0.0 in.
Width of Depression, W	= 1.0 ft.	= 4.0 ft.
Perimeter of Drain Opening, P	= 1.208 ft.	= 8.75 ft.
Clear Area of Grate Opening, A_{clear}	= 100% * W_d * L = 0.1823 sq. ft.	= 90% * W_d * L = 2.700 sq. ft.
Area of Downspout Opening, A_O	= 0.1823 sq. ft.	= 0.1636 sq. ft.
Depth of Drain Box, d	= 0.0 in.	= 6.5 in.
Splash-over Velocity, V_0	= 4.5 ft/s *P-1-7/8 grate*	= 1.9 ft/s *Reticuline grate* (Chart 5B)

The Tube Drain is conservatively modeled as a Parallel Grate, P-1-7/8 (in most situations, all frontal flow will be intercepted). The Aesthetic Deck Drain is modeled as a Reticuline Grate.

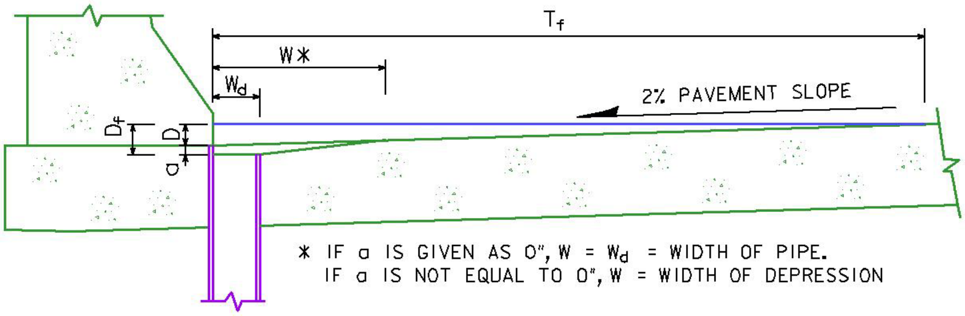


Figure 2: Layout of Standard Inlet, BSB SS 4380 Series

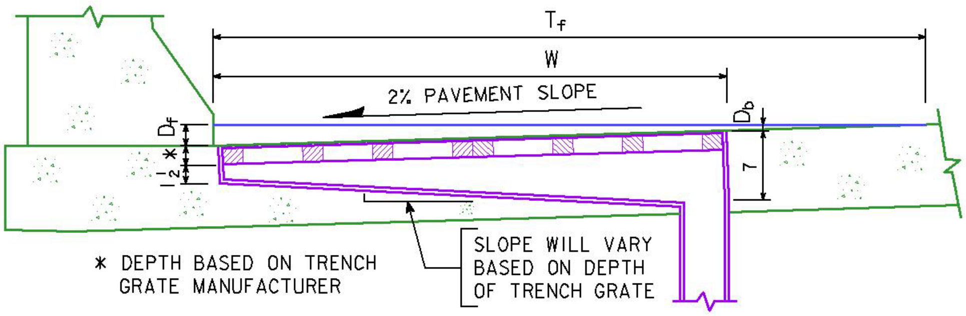


Figure 3: Layout of Aesthetic Deck Drain, BSB SS 1054

Vertical Profile:

Vertical Point of Intersection, VPI = ##+##.#
Vertical Point of Curvature, VPC = ##+##.# (calculated by spreadsheet)
Vertical Point of Tangency, VPT = ##+##.# (calculated by spreadsheet)

Length of Vertical Curve, L of VC = # ft. or m
Elevation, e = #.## ft. or m

Station at Start of Bridge, StaSB = ##+##.#
Station at End of Bridge, StaEB = ##+##.#

Grade, G_1 or G_2 = # % (calculated by spreadsheet)

For a bridge on a vertical tangent, two VPIs must be known in order to determine g_1. For a bridge on a vertical curve, three VPIs and the L of VC must be known in order to determine g_1, g_2, VPC and VPT. The spreadsheet will calculate these values and S_L for any point along the vertical profile. For more information on vertical curve calculations, see the Design Bureau's Design Manual, Sec. 2B-01.

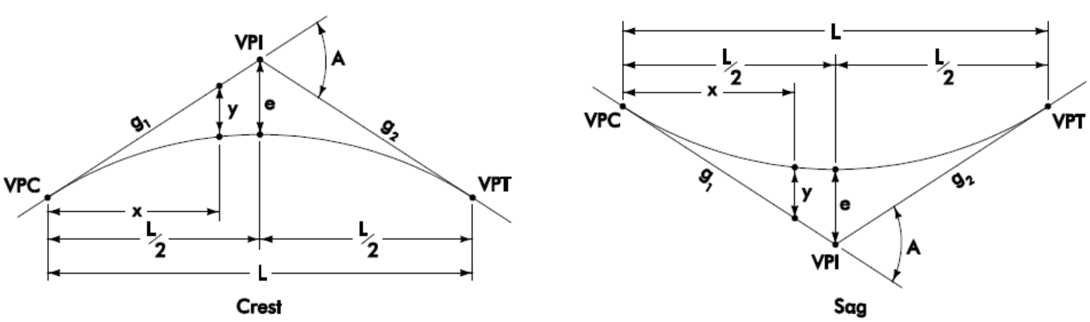


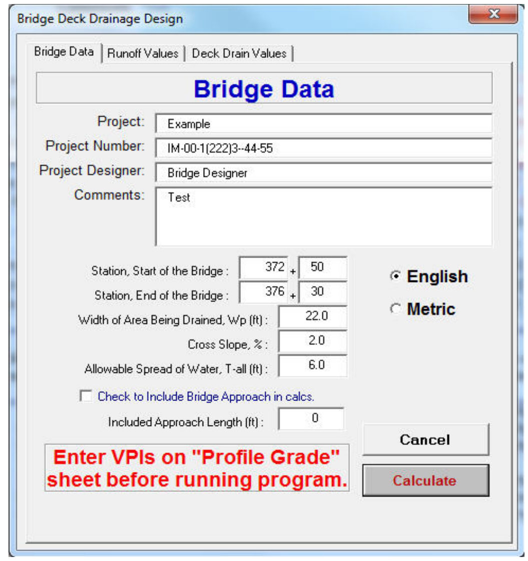
Figure 4: Symmetrical Vertical Curves

Drainage Equations:

Note: Take care to convert "a" and "d" values (given in inches or millimeters) to appropriate primary unit (feet or meters) for use in equations. Conversions are not shown in following equations. The spreadsheet will make appropriate conversions.

Description	Equation	HEC-22 Reference
$Q_t = Q_{total}$ Total discharge an area	$Q_{total} = Q_t = \frac{C * i * A}{A_{constant}} + Q_{bypass}$	
T_f Width of Flow. Only valid for T over constant S_x.	$T_f = \left[\frac{Q_t * n}{K_m S_x^{5/3} S_L^{0.5}}\right]^{0.375}$	Eq. 4-2
D_f Depth of Flow, At Edge of Gutter	$D_f = T_f * S_x + a$	
D_b Depth of Flow, At Edge of Scupper	$D_b = D_f - W_d * S_w$	
D_s Depth of Flow, At Edge of Depression	$D_s = (T_f - W) * S_x = D_f - W * S_w$	
$Q_f = Q_t$ Quantity of Flow. Only valid for Q over constant S_x.	$Q_f = \frac{K_m}{n} S_L^{0.5} S_x^{5/3} T_f^{8/3}$ $Q_f = \frac{K_m}{n * S_x} S_L^{0.5} D_f^{8/3}$	Eq. 4-2
Q_s Quantity of Side Flow above Scupper	$Q_s = Q_t * (1 - E_0)$ $Q_s = \frac{K_m}{n} S_L^{0.5} S_x^{5/3} (T_f - W)^{8/3}$ $Q_s = \frac{K_m}{n * S_x} S_L^{0.5} D_s^{8/3}$	Ex. 4-2
Q_w Quantity of Flow across depression W. Use with a ≠ 0 ($S_w > S_x$).	$Q_w = \frac{K_m}{n * S_w} S_L^{0.5} (D_f^{8/3} - D_s^{8/3}) = E_0 * Q_t$	
V Average Velocity of Flow, given a = 0	$V = \frac{K_V}{n} S_L^{0.5} S_x^{2/3} T_f^{2/3}$	Eq. 4-13
V Average Velocity of Flow, given a ≠ 0	$V = \frac{Q_f}{A_f} = \frac{Q_f}{0.5 * D_f * T_f * S_x + 0.5 * a * W}$	Ex. 4-7
E_0 Ratio of frontal flow to total flow no gutter depression, constant S_x	$E_0 = Q_w / Q_t$ $E_0 = 1 - (1 - {}^{W}/_{T_f})^{8/3} \leq 1.0$	Eq. 4-16
E_0 Ratio of frontal flow to total flow with gutter depression, W = width of depression	$E_0 = 1/[1 + \frac{S_w/S_x}{\left[1 + \frac{S_w/S_x}{{}^{T_f}/_{W} - 1}\right]^{8/3} - 1}] \leq 1.0$	Eq. 4-4

Description	Equation	HEC-22 Reference
E'_0 Ratio of frontal flow to total flow for grates in other composite cross sections, $W_d < W$	A'_w = Flow area across grate width W_d only A_w = Flow area in depressed gutter width W $E'_0 = E_0 * \frac{A'_w}{A_w}$	Eq. 4-20a
R_f Ratio of intercepted frontal flow to total frontal flow	$R_f = 1 - K_f * (V - V_0) \leq 1.0$	Eq. 4-18
R_s Ratio of intercepted side flow to total side flow	$R_s = 1/(1 + \frac{K_s V^{1.8}}{S_x L^{2.3}}) \leq 1.0$ **Set to 0 for Bridge Drainage**	Eq. 4-19
$E = E_{inlet}$ Efficiency of grate as a ratio of captured to total flow.	$E = Q_i/Q_t$ $E = R_f * E_0 + R_s * (1 - E_0)$ given that $R_s = 0$, $E = R_f * E_0$	Eq. 4-20
$Q_i = Q_{intercept}$ Intercept (Captured) Flow at Drain on Grade S_L	$Q_i = Q * [R_f * E_0 + R_s * (1 - E_0)]$ given that $R_s = 0$ $\rightarrow Q_i = Q * E_0 * R_f$	Eq. 4-21
$Q_b = Q_{bypass}$ Bypass Flow at Drain	$Q_b = Q * (1 - E_0 * R_f)$	
$Q_d = Q_{downspout}$, Q_{orif} Flow Capacity of Downspout and Intercept Flow at Drain in Sump Location (orifice flow)	$Q_d = C_O * A_O * (2 * g * H_O)^{1/2}$	Eq. 4-27 Eq. 8-18
Q_{weir} Intercept Flow at Drain in Sump Location (weir flow)	$Q_i = C_w * P * H_O{}^{1.5}$	Eq. 4-26
H_O, Eff. Head at Center of Downspout, Standard Tube Drain	Per standard, tube is mounted flat. Therefore, average height across W_d is given as: $H_O = D_f$	
H_O, Eff. Head at Center of Downspout, Aesthetic Deck Drain	Assume drain box is full $H_O = d + D_b$	
L_C Maximum spacing on flat bridge	$L_C = \frac{1312}{(n * C * i * W_p)^{0.67}} S_x^{1.44} T_{all}^{2.11}$	HEC-21, Eq. 24
P Minimum perimeter required within distance L_C of flat portion of bridge	$P = \frac{(C * i * W_p)^{0.33} T^{0.61}}{102.5 * S_x^{0.06} * n^{0.67}}$	HEC-21, Eq. 25



<u>Spreadsheet Setup</u>:

- Enter the project profile on the "Profile Grade" sheet. You must enter at least two VPIs, and the spreadsheet will calculate the appropriate g_1, g_2, PVC, PVT, and S_L values.

VPI STA	VPI ELEV	L of VC
325+00.00	550.000	0.000
350+00.00	600.000	1000.000
375+00.00	550.000	
		0.000

- Press "Push Button to Run Program" on the "Drains" sheet. Enter the Project Name, Project Number, Designer, and Comments. Enter the starting and the ending station of the bridge and the W_p, S_x, and T_{all} values. The program can include an extra length for the approaches if desired (this value can be changed later without re-running the program). Selecting "English" or "Metric" will change units and recommended values to the correct system.

- Check the variables and settings on the "Deck Drain Values" Tab. Typical and recommended values are given for the Standard Tube and Aesthetic deck drains. For a conservative analysis, use a = 0 (no depression at drain). The designer should take care to completely understand the calculations before deviating from the recommended values.

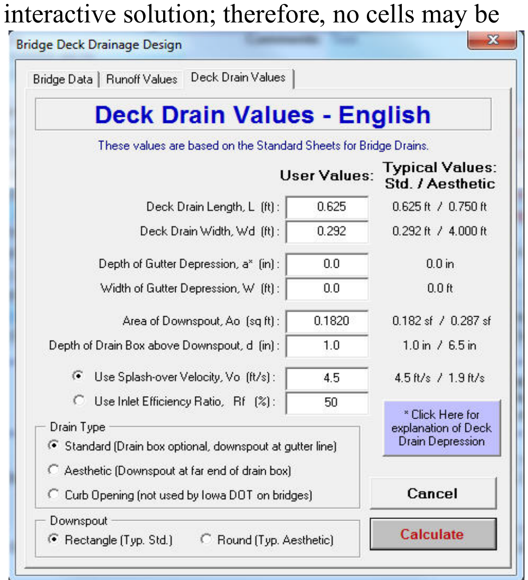
- When the "Calculate" button is pressed, the program will begin analysis by finding the high point of the bridge and working forwards and backwards from that point. The program will inform the user if drains are required (maximum spread is exceeded), and will then ask for the number of drains and the spacing. The program will give some guidance to the user as to maximum spacing between drains.

- After the program has been run, it will unlock cells that may be changed by the user without re-running the program. These cells are indicated by blue highlighting.

    - Any changes to profile grade or the number of drains requires the user to re-run the program.

    - An analysis with a deck drain depression (a≠0) requires an interactive solution; therefore, no cells may be changed after processing.

    - For other drains, the drain spacing, efficiency (if applicable), allowable spread of water, and length of approach may be adjusted after processing.



Steps for Hydraulic Analysis:

After completing the dialog boxes shown above, the spreadsheet will complete the following analysis steps. The program will first test the Qtotal and Tf for the entire bridge to determine if drains are hydraulically necessary. If so, the program will prompt the user for the number of drains and for the Spacing (Step 2) between drains. The same steps apply if the user wishes to do hand-calculations.

Steps for Standard Tube Drain or Aesthetic Drain on Grade

These inlets are treated as a grate inlets. For the Standard Tube Drain, R_f will typically equal 1 (all frontal flow is captured). The capacity of the grate should be checked against the capacity of the downspout.

1) Determine high point of bridge (starting point for analysis). If the bridge is entirely uphill or downhill, start at the high end of bridge and work towards the opposite end. If the bridge is located on a crest or sag curve, the analysis will need to be done twice. For a crest bridge, start at the high point and work towards the start of the bridge, then begin again at the high point and work towards the end of the bridge. For a bridge with a low point, start at the beginning and work towards the middle, noting the final flow at the low point. Then begin again at the end of the bridge, work towards the middle, and add the final flow to the flow from the first half to analyze the sump drain at the low point.

$$Slope\ at\ Sta\ "X" = \frac{g_1 - g_2}{L\ of\ VC} * (Sta - VPC) + g_1$$

As the bridge end drain is located past the double-reinforced approach section, and the approaches are curbed, it would be appropriate to include the length of approaches in the analysis. If the Length of Approach is specified, the spreadsheet will add this length to either the first or last Spacing, depending on the slope of the bridge. The user may not place a drain on an approach.

2) Spacing: Input spacing from previous drain or high point to current drain. The program will alert the user as to the maximum distance before the allowable spread is exceeded. For guidance as to drain efficiency, the program will also calculate the distance until the capacity of the gutter exceeds the capacity of the downspout.

3) Q_{total}: Calculate total discharge at Drain based on bypass from upstream inlet and spacing to drain.
$Q_t = (C * i * A) / A_{constant} + Q_{bypass}$
$A = W_p * Distance$

4) T_f: Find Total Width of Flow for Discharge.
If $a = 0$ ($S_w = S_x$), T_f can be calculated directly from the gutter flow equation:
$T_f = (Q_f * n / (K_m * S_x^{5/3} * S_L^{0.5}))^{0.375}$

If $a \neq 0$, T_f must be found interactively by assuming a Q_s and:
finding T_s for the Q_s, $T_s = (Q_s * n / (K_m * S_x^{5/3} * S_L^{0.5}))^{0.375}$
calculating the total T_f, $T_f = T_s + W$
calculating the E_0 for this configuration,
$E_0 = 1/\{1+(S_w/S_x)/[(1+(S_w/S_x)/(T/W-1))^{8/3}-1]\}$
re-calculating Q_s. $Q_s = (1 - E_0) * Q_t$
Compare this Q_s to the assumed Q_s, adjust, and repeat until the values match.

If $T_f > T_{all}$, spacing is too large and the distance should be shortened.

5) V: Find Velocity of Flow, Q/A
If $a = 0$, then $V = K_v / n * S_L^{0.5} * S_x^{5/3} * T_f^{2/3}$, or
$V = Q_t / (0.5 * T_f^2 * S_x)$
If $a \neq 0$, then $V = Q_t / (0.5 * T_f^2 * S_x + 0.5 * a * W)$

6) E_0: Find ratio of frontal flow to total flow
If $a = 0$, then $E_0 = 1 - (1 - W / T_f)^{8/3}$
If $a \neq 0$, then $E_0 = 1/\{1+(S_w/S_x)/[(1+(S_w/S_x)/(T/W-1))^{8/3}-1]\}$
If $W_d \neq W$, then use E'_0 in place of E_0
$E'_0 = E_0 * A'_w/A_w$
$= E_0*(W_d*(D_f+W_d*S_w)/2)/(W*(D_f+D_b)/2)$

7) R_f: Find ratio of captured frontal flow to frontal flow
$R_f = 1 - K_f * (V - V_0) \leq 1.0$

8) E_{inlet}: Find Efficiency of Inlet $\quad E_{inlet} = E_0 * R_f$

9) Q_{inlet}: Calculate Intercepted Flow at Drain 1 $\quad Q_i = E * Q = Q * E_0 * R_f$
If including a E_{deb} term reduction, then $\quad Q_i = Q_i * E_{deb}$

10) $Q_{downspout}$: Find Flow Capacity of Downspout, $\quad Q_d = C_O * A_O * (2 * g * H_O)^{0.5}$
If Standard Drain, then $\quad H_O = D_f = T_f * S_x + d$
If Aesthetic Drain, then $\quad H_O = D_b = T_f * S_x + d - W_d * S_w$

If $Q_d \le Q_i$, then $\quad Q_i = Q_d$

11) Q_{bypass}: Evaluate Bypass Flow $\quad Q_b = Q - Q_i$

12) Repeat for next Distance, adding Q_b to the pavement runoff to the next drain.

<u>Steps for Standard Tube Drain or Aesthetic Drain at Sump Location</u>

The capacity required at the drain is equal to the total flow entering the sag from both directions. The flow is compared to the weir and orifice flows to determine the correct model, and the spread generated by that drain flow is then determined. For Curb Inlets at sump locations, HEC-22 shows that Weir flow occurs up to a depth equal to the height of the curb opening, and Orifice flow occurs with depths greater than 1.4 times the height of curb opening. Between these two depths, transition flow occurs. A similar division and transition zone occurs with Grate Inlets. However, HEC-22 does not give approximate depth limits for these flows; it is dependent on the grate configuration and relative values of P and A_{clear}. By reviewing Equation 4-26 and Chart 9b, it appears that Weir Flow occurs up to a Depth ≈ $0.1875*P^{2/3}$. Orifice Flow begins at a Depth ≈ $0.67*A_{clear}^{0.5}$. For grates that are shorter than they are wide (as in the Aesthetic deck drain), the Weir Flow will be limited by the Orifice Flow curve at the same depth. See Figure 5 below.

The drain discharge flow is also limited by the capacity of the downspout, assuming it operates in Orifice flow.

1) Distance: Calculate total spacing from both previous drains to sag drain (flow will come from both directions).

2) Q_{total}: Calculate total discharge at Drain based on bypass from upstream inlets and spacings to drain. $\quad Q_t = (C * i * A) / A_{constant} + Q_{bypass\text{-}1} + Q_{bypass\text{-}2}$
$\quad A = W_p * (\text{Distance1} + \text{Distance2})$

3) $Q_{downspout}$: Find Flow Capacity of Downspout, $\quad Q_d = C_O * A_O * (2 * g * H_O)^{0.5}$
If Standard Drain, then $\quad H_O = D_f = T_f * S_x + d$
If Aesthetic Drain, then $\quad H_O = D_b = T_f * S_x + d - W_d * S_w$
Assuming $T_f = T_{all}$, Solve for Q_d. If $Q_d > Q_t$, add more flanking inlets to reduce flow at sump location, or increase the size of the downspout.

4) Q_{weir}, maximum: Determine the maximum capacity of weir flow.
$Q_{weir\text{-}max}$ occurs approximately when $\quad D_{weir} = 0.1875 * P^{2/3}$
The intersection of the weir and orifice flow curves can be found by setting $Q_{weir} = Q_{orif}$ and solving for D $\quad D_{weir} \le (C_O * A_{clear} * (2 * g)^{0.5}) / (C_w * P)$

The Q at this depth can be found from Equation 4-26 $Q_{weir} = C_w * P * D_{weir}^{1.5}$

<u>For a Standard Tube Drain</u>

$D_{weir} = 0.1875 * 1.208^{2/3}$

$\leq 0.67 * 0.1823 * (2*32.2)^{0.5} / (3 * 1.208)$

$D_{weir} = 0.213 \leq \cancel{0.270}$ ft.

$Q_{weir} = 3.0 * 1.208 * 0.213^{1.5} = 0.36$ cfs

<u>For an Aesthetic Deck Drain</u>

$D_{weir} = 0.1875 * 8.75^{2/3}$

$\leq 0.67 * 2.7 * (2*32.2)^{0.5} / (3 * 8.75)$

$D_{weir} = \cancel{0.796} \leq 0.553$ ft.

$Q_{weir} = 3.0 * 8.75 * 0.553^{1.5} = 10.80$ cfs

Based on these calculations, for the typical drainage volumes on IDOT bridges, the Aesthetic Deck Drain should always be in weir flow.

5) Q_{orif}, minimum: Determine the minimum capacity of orifice flow.

$Q_{orif\text{-}min}$ occurs approximately when $D_{orif} = 0.67 * A_{clear}^{0.5}$

The Q at this depth can be found from Equation 4-26 $Q_{orif} = C_O * A_{clear} * (2 * g * D_{weir})^{0.5}$

<u>For a Standard Tube Drain</u>

$D_{orif} = 0.67 * 0.1823^{0.5} = 0.286$ ft

$Q_{orif} = 0.67 * 0.1823 * (2 * 32.2 * 0.286)^{0.5}$

$Q_{orif} = 0.52$ cfs

<u>For an Aesthetic Deck Drain</u>

$D_{orif} = 0.67 * 2.70^{0.5} = 1.101$ ft

$Q_{orif} = 0.67 * 2.70 * (2 * 32.2 * 1.101)^{0.5}$

$Q_{orif} = 15.23$ cfs

Based on these calculations, for the typical drainage volumes on IDOT bridges, the Aesthetic Deck Drain should always be in weir flow.

6) D_{inlet}: The actual capacity of the inlet is equal to the flow at the sump location, Q_{total}. The average depth of water across the inlet generated by this flow can be determined by the characteristics of the inlet.

If $Q_{total} \leq Q_{weir\text{-}max}$ occurs, then $D_{inlet} = D_{weir} = (Q_{total} / (C_w * P))^{2/3}$

If $Q_{total} \geq Q_{orif\text{-}min}$ occurs, then $D_{inlet} = D_{orif} = (Q_{total} / (C_O * A_{clear} * (2 * g)^{0.5}))^2$

If Q_{total} is in transition flow, find D_{inlet} as a ratio between $D_{weir\text{-}max}$ and $D_{orif\text{-}max}$.

$$D_{inlet} = (Q_{total} - Q_{weir\text{-}max}) * \frac{(D_{orif\text{-}min} - D_{weir\text{-}max})}{(Q_{orif\text{-}min} - Q_{weir\text{-}max})} + D_{weir\text{-}max}$$

7) D_f : Determine the depth of water at the curb (D_{inlet} is the average depth across the inlet).

$$D_f = D_{inlet} + S_w * W_d / 2$$

8) T_f : Determine the spread at the sump location.

If $S_w = S_x$, $T_f = D_f * S_x$

If $S_w \neq S_x$, $T_f = (D_f - W) * S_x + W * S_x$

If $T_f > T_{all}$, then the sump drain is insufficient. The sump drain should be modified or additional flanking inlets should be used to intercept the flow.

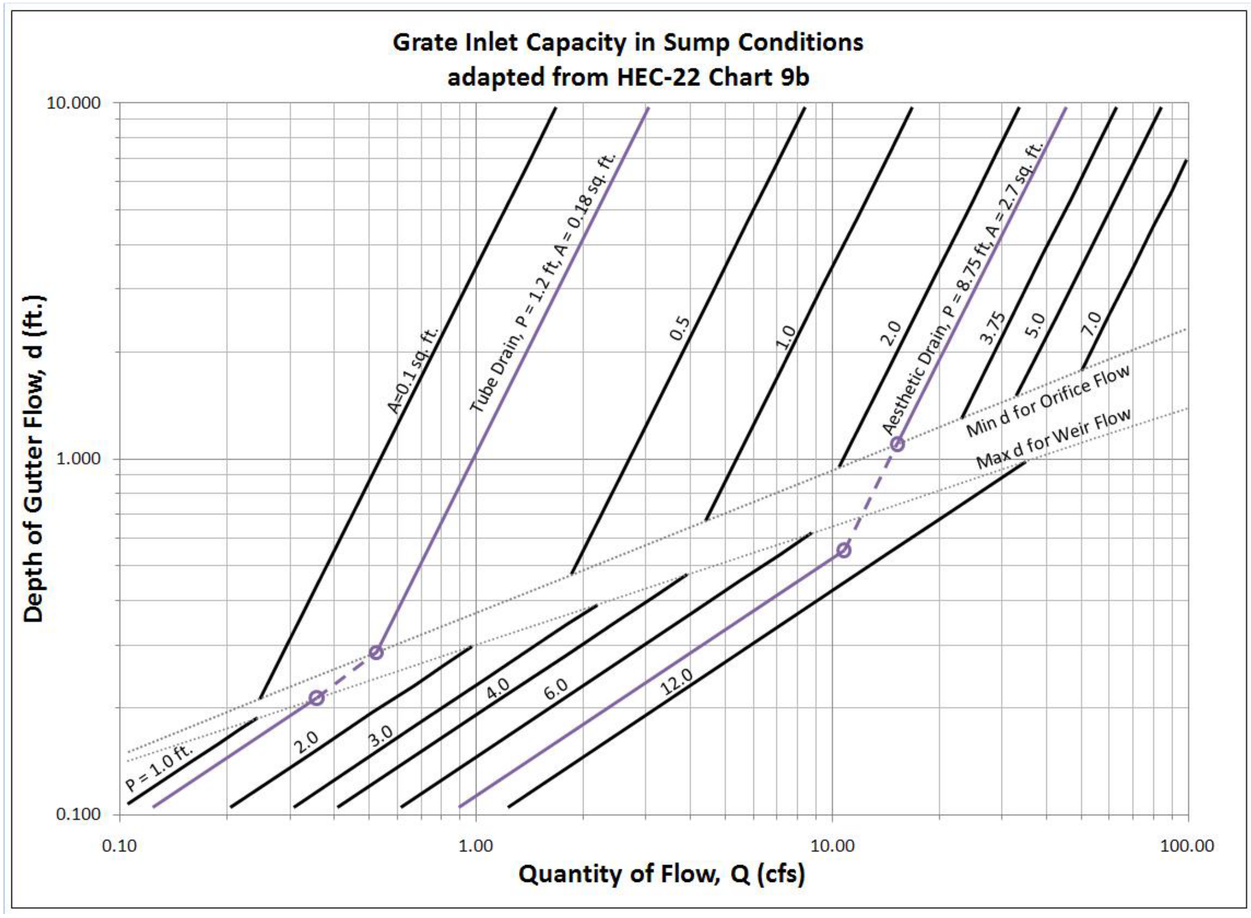


Figure 5: Grate Inlet Capacity in Sump Conditions

Additional Checks:

- Spacing of First Drains

  The maximum spacing between inlets is limited by a flat condition (S_L<0.3%). This occurs on flat profiles and at the top of a vertical curve (at the bottom of a vertical curve, the spacing is controlled by the sump condition requirements). The maximum spacing can be found using HEC-21 Eq. 24.

$$L_C = \frac{1312}{(n * C * i * W_p)^{0.67}} S_x^{1.44} T_{all}^{2.11}$$

  This requires a minimum inlet perimeter based on HEC-21 Eq. 25.

$$P = \frac{(C * i * W_p)^{0.33} T^{0.61}}{102.5 * S_x^{0.06} * n^{0.67}}$$

- Spacing of Flanking Drains at Sump Locations

  Flanking Inlets serve to discharge the flow at the sump location should the primary drain become clogged. Therefore, the flanking inlets should not be included as part of the hydraulic analysis.

  - The BDM Article 5.8.4.2.1 recommends placing the flanking drains where the longitudinal slope S_L = 0.3% on each side of the sag point. Considering that K is the rate of vertical curvature, the spacing, x, to a given S_L from the sag point is given as:

$$x = S_L * K$$

S_L is in percent.

- HEC-22 Sec. 4.4.6.3 illustrates the maximum spacing of flanking inlets. If the flanking inlets are the same dimension as the primary inlet, they will each intercept one-half the design flow when they are located so that the depth of ponding at the flanking inlets is 63% of the depth of ponding at the low point. The spacing, x, to achieve this depth is given as:

  $$x = \sqrt{74 * d_i * K}$$

  K is the rate of vertical curvature, given as:

  $$K = \frac{L\ of\ VC}{G_2 - G_1} \leq 167$$

  G_2 and G_1 are in percent, and 167 is the K limit for drainage from AASHTO.

For comparison purposes, the x values for the minimum K at various design speeds are given in Figure 6. These K values are taken from the Design Bureau's Design Manual, Sec. 6D-5, Table 3. Since these are minimum K values, and in most cases the actual K value from the profile vertical curve on a bridge will be higher, the values in this table may be considered conservative. The flanking inlets should not be placed farther away than the distance indicated by the above equations. In general, it will be sufficient to place the flanking inlets 10-15 feet from the sag point.

Design Speed (mph)	**Min. K for Stopping Sight Distance**	**Distance from Sag Point to S_L = 0.3% (ft.)**	**Distance from Sag Point to 63% d_i (ft.)**		
			T_{all} = 6 ft.	**T_{all} = 8 ft.**	**T_{all} = 10 ft.**
30	37	12	19	21	24
35	49	15	21	25	27
40	64	20	24	28	31
45	79	24	27	31	35
50	96	29	30	34	38
55	115	35	32	37	42
60	136	41	35	41	45
65	157	48	38	44	49
70	181	55	41	47	52

Figure 6: Maximum Distances to Flanking Inlets