11.12 Hydraulic Grade Line

11.12.1 Introduction

The hydraulic grade line (HGL) is the last important feature to be established relating to the hydraulic design of storm drains. This gradeline aids the designer in determining the acceptability of the proposed system by establishing the elevations along the system to which the water will rise when the system is operating from a flood of design frequency.

In general, if the HGL is above the crown of the pipe, pressure flow hydraulic calculations are appropriate. Conversely, if the HGL is below the crown of the pipe, open channel flow calculations are appropriate. A special concern with storm drains designed to operate under pressure flow conditions is that inlet surcharging and possible manhole lid displacement can occur if the hydraulic grade line rises above the ground surface. A design based on open channel conditions must be carefully planned as well, including evaluation of the potential for excessive and inadvertent flooding created when a storm event larger than the design storm pressurizes the system. As hydraulic calculations are performed, frequent verification of the existence of the desired flow condition should be made. Storm drain systems can often alternate between pressure and open channel flow conditions from one section to another.

The detailed methodology employed in calculating the HGL through the system begins at the system outfall with the tailwater elevation. If the outfall is an existing storm drain system, the HGL calculation must begin at the outlet end of the existing system and proceed upstream through this inplace system, then upstream through the proposed system to the upstream inlet. The same considerations apply to the outlet of a storm drain as to the outlet of a culvert. See Figure 8-4 for a sketch of a culvert outlet which depicts the difference between the HGL and the energy grade line (EGL). Usually it is helpful to compute the EGL first, then subtract the velocity head ($V^2/2g$) to obtain the HGL.

11.12.2 Tailwater

For most design applications, the tailwater will either be above the crown of the outlet or can be considered to be between the crown and critical depth (d_c). To determine the EGL, begin with the tailwater elevation or $(d_c + D)/2$, whichever is higher, add the velocity head for full flow and proceed upstream to compute all losses such as exit losses, friction losses, junction losses, bend losses and entrance losses as appropriate.

An exception to the above might be a very large outfall with low tailwater when a water surface profile calculation would be appropriate to determine the location where the water surface will intersect the top of the barrel and full flow calculations can begin. In this case, the downstream water surface elevation would be based on critical depth or the tailwater, whichever is higher.

When estimating tailwater depth on the receiving stream, the prudent designer will consider the joint or coincidental probability of two events occurring at the same time. For the case of a tributary stream or a storm drain, its relative independence may be qualitatively evaluated by a comparison of its drainage area with that of the receiving stream. A short duration storm which causes peak discharges on a small basin may not be critical for a larger basin. Also, it may safely be assumed that if the same storm causes peak discharges on both basins, the peaks will be out of phase. To aid in the evaluation of joint probabilities, refer to Section 8.3.6, Table 8-3, Joint Probability Analysis, Chapter 8, Culverts. For example, a main stream (receiving waters) and tributary (storm drain outfall) have a drainage area ratio of 100 to 1 and a 10-year design is required for the storm drain system. Table 8-3 indicates that:

1. When a 10-year storm is applied to the tributary, the highwater of the main stream should be determined for a 5-year storm frequency.
2. A 10-year highwater on the main stream should be applied to a 5-year storm frequency on the tributary.

The analyses should include any additional drainage area that the outfall receives between the storm drain outlet and the receiving waters.

11.12.3 Exit Loss

The exit loss is a function of the change in velocity at the outlet of the pipe. For a sudden expansion such as an endwall, the exit loss is:

$$H_o = 1.0 \left[\frac{V^2}{2g} - \frac{V_d^2}{2g} \right] \quad \textbf{(11.19)}$$

Where: V = average outlet velocity, m/s (ft/s)
V_d = channel velocity downstream of outlet, m/s (ft/s)

Note that when $V_d = 0$ as in a reservoir, the exit loss is one velocity head. For part full flow where the pipe outlets in a channel with moving water, the exit loss may be reduced to virtually zero.

11.12.4 Bend Loss

The bend loss coefficient for storm drain design is minor but can be evaluated using the formula:

$$h_b = 0.0033\ (\Delta)\ (V_o^2 / 2g) \quad \textbf{(11.20)}$$

Where: Δ = angle of curvature in degrees

11.12.5 Pipe Friction Losses

The friction slope is the energy gradient in m/m (ft/ft) for that run. The friction loss is simply the energy gradient multiplied by the length of the run. Energy losses from pipe friction may be determined by rewriting the Manning's equation with terms as previously defined:

$$S_f = [Qn/A\,R^{2/3}]^2 \qquad (S_f = \left[Qn/1.486AR^{2/3}\right]^2) \quad \textbf{(11.21)}$$

The head losses due to friction may be determined by the formula:

$$H_f = S_f\,L \quad \textbf{(11.22)}$$

The Manning's equation can also be written to determine friction losses for storm drains as follows:

$$H_f = 6.35\ n^2\ V^2 L / D^{4/3} \qquad (H_f = 2.88 n^2 V^2 L / D^{4/3}) \qquad \textbf{(11.23)}$$

$$H_f = \frac{19.62\ n^2\ L}{R^{4/3}} \left(\frac{V^2}{2g} \right) \qquad (H_f = \frac{29 n^2 L}{R^{4/3}} \left[\frac{V^2}{2g} \right]) \qquad \textbf{(11.24)}$$

Where: H_F = total head loss due to friction, m (ft)
n = Manning's roughness coefficient (See Appendix A, Chapter 8, Culverts)
D = diameter of pipe, m (ft)
L = length of pipe, m (ft)
V = mean velocity, m/s (ft/s)
R = hydraulic radius, m (ft)
g = 9.81 m/s^2 (32.2 ft/s^2)
S_f = slope of hydraulic grade line, m/m (ft./ft.)

11.12.6 Structure Losses

The head loss encountered in going from one pipe to another through a structure (catch basin, manhole, etc.) is commonly represented as being proportional to the velocity head at the outlet pipe. Using K to signify this constant of proportionality, the energy loss is approximated as K (V_o^2/2g). Experimental studies have determined that the K value can be approximated as follows:

$$* K = K_o C_D C_d C_Q C_p C_B \qquad \textbf{(11.25)}$$

Where: K = adjusted loss coefficient
K_o = initial head loss coefficient based on relative manhole size.
C_D = correction factor for pipe diameter (pressure flow only)
C_d = correction factor for flow depth (non-pressure flow only)
C_Q = correction factor for relative flow
C_B = correction factor for benching
C_p = correction factor for plunging flow

* In some cases, the intent of the methodology is to compare the size of one pipe to another pipe (or to the size of the structure). In these cases an equivalent diameter is used, which is computed from the full area of the pipe or structure.

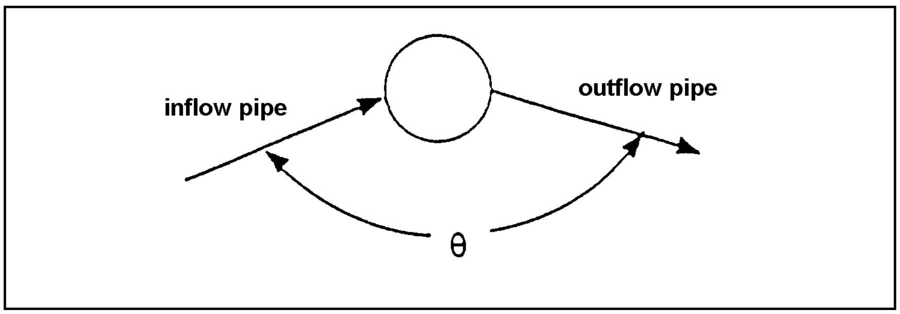
Relative Manhole Size

K_o is estimated as a function of the relative structure size and the angle of deflection between the inflow and outflow pipes.

$$K_o = 0.1(b/D_o)(1 - \sin\theta) + 1.4(b/D_o)^{0.15}\sin\theta \qquad \textbf{(11.26)}$$

Where: θ = the angle between the inflow and outflow pipes
b = structure diameter, mm (in)
D_o = outlet pipe diameter, mm (in)

Deflection Angle



Pipe Diameter

A change in head loss due to differences in pipe diameter is only significant in pressure flow situations when the depth in the structure to outlet pipe diameter ratio, d/D_o, is greater than 3.2 otherwise C_D is set equal to 1.0. Therefore, it is only applied in such cases.

$$C_D = (D_0 / D_i)^3 \qquad \textbf{(11.27)}$$

Where: D_i = incoming pipe diameter, mm (in)
D_o = outgoing pipe diameter, mm (in)

Flow Depth

The correction factor for flow depth is significant only in cases of free surface flow or low pressures, when d/D_o ratio is less than 3.2 and is only applied in such cases. In cases where this ratio is greater than 3.2, C_d is set equal to 1.0. Water depth in the manhole is approximated as the level of the hydraulic gradeline at the upstream end of the outlet pipe. The correction factor for flow depth, C_d, is calculated by the following:

$$C_d = 0.5(d/D_o)^{0.6} \qquad \textbf{(11.28)}$$

Where: d = water depth in structure above outlet pipe invert, mm (in)
D_o = outlet pipe diameter, mm (in)

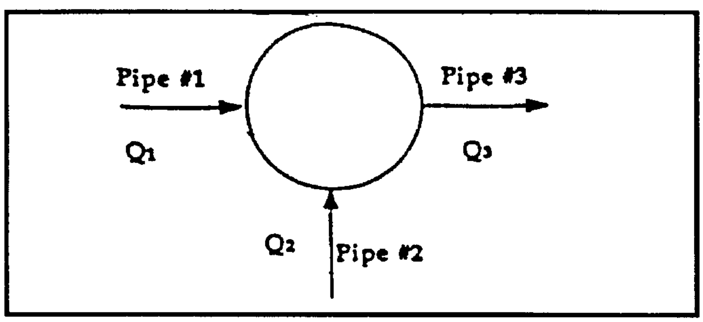
Relative Flow

The correction factor for relative flow, C_Q, is a function of the angle of the incoming flow as well as the percentage of flow coming in through the pipe of interest versus other incoming pipes. The correction factor is only applied to situations where there are three or more pipes entering the structure at approximately the same elevation. Otherwise, the value of C_Q is equal to 1.0. It is computed as follows:

$$C_Q = (1 - 2\sin\theta)\,(1 - \frac{Qi}{Qo})^{0.75} + 1 \qquad \textbf{(11.29)}$$

where: C_Q = correction factor for relative flow
θ = the angle between the inflow and outflow pipes (degrees)
Q_i = flow in the inflow pipe, m^3/s (ft^3/s)
Q_o = flow in the outlet pipe, m^3/s (ft^3/s)

As can be seen from the equation, C_Q is a function of the angle of the incoming flow as well as the percentage of flow coming in through the pipe of interest versus other incoming pipes. To illustrate this effect, consider the manhole shown in the Figure and assume the following two cases to determine the impact of pipe 2 entering the manhole.



Relative Flow Effect

Case 1:

Q_1= 0.09 m^3/s, Q_2= 0.03 m^3/s, Q_3= 0.12 m^3/s then C_Q = 1.35

$C_{Q3\text{-}1} = (1\text{-}2 \sin 180^o)(1 - 0.09/0.12)^{.75} + 1 = 1.35$

Case 2:

Q_1= 0.03 m^3/s, Q_2= 0.09 m^3/s, Q_3= 0.12 m^3/s then C_Q = 1.81

$C_{Q3\text{-}1} = (1\text{-}2 \sin 180^o)(1 - 0.03/0.12)^{.75} + 1 = 1.81$

Plunging Flow

The correction factor for plunging flow, C_p, is calculated by the following:

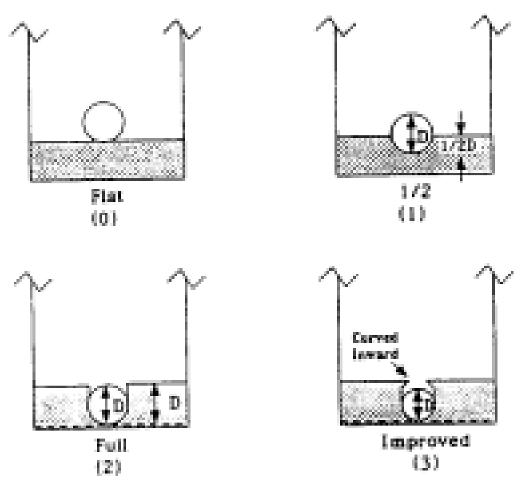
$$C_p = 1 + 0.2 \left[\frac{h}{D_o}\right] \left[\frac{(h-d)}{D_o}\right] \qquad \textbf{(11.30)}$$

Where: C_p = correction for plunging flow
h = vertical distance of plunging flow from flow line of higher elevation incoming pipe to the center of outlet pipe, m (ft)
D_o = outlet pipe diameter, m (ft)
d = water depth in structure above outlet pipe invert, m (ft)

This correction factor corresponds to the effect of another inflow pipe or surface flow from an inlet, plunging into the structure, on the inflow pipe for which the head loss is being calculated. Using the notations in the above figure for the example, C_p is calculated for pipe # 1 when pipe # 2 discharges plunging flow. The correction factor is only applied when $h > d$, otherwise, the value of C_p is equal to 1.0. Additionally, the correction factor is only applied when a high elevation flow plunges into the structure that has both an inflow and outflow in the bottom of the structure.

Benching

The correction for benching in the structure, C_B, is obtained from Table 11-9. Benching tends to direct flows through the structure, resulting in reductions in head loss. For flow depths between the submerged and unsubmerged conditions, a linear interpolation is performed.



Schematic Representation Of Benching Types

Table 11-9 Correction for Benching

Bench Type	**Correction Factors, C_B**	
	Submerged*	Unsubmerg-ed**
Flat floor	1.00	1.00
Half Bench	0.95	0.15
Full Bench	0.75	0.07
Improved	0.40	0.02
*pressure flow, $d/D_o > 3.2$ **free surface flow, $d/D_o < 1.0$		

Summary

In summary, to estimate the head loss through a structure from the outflow pipe to a particular inflow pipe, multiply the above correction factors together to get the head loss coefficient, K. This coefficient is then multiplied by the velocity head in the outflow pipe to estimate the minor loss for the connection.

11.12.7 Hydraulic Grade Line Design Procedure

The equations and charts necessary to manually calculate the location of the hydraulic gradeline are included in this chapter. A step by step procedure is given to manually compute the HGL. Table 11-10 can be used to document the procedure.

If the HGL is above the pipe crown at the next upstream structure, pressure flow calculations are indicated; if it is below the pipe crown, then open channel flow calculations should be used at the upstream structure. The process is repeated throughout the storm drain system. If all HGL elevations meet the 0.3m (1 ft) freeboard from top of grate requirement, then the hydraulic design is adequate. If the HGL exceeds this 0.3m (1 ft) freeboard, then adjustments to the trial design must be made to lower the water surface elevation.

See Figure 11-12 for a sketch depicting the use of energy losses in developing a storm drain system.

Step 1 Enter in Col. 1 the station for the junction immediately upstream of the outflow pipe. HGL computations begin at the outfall and are worked upstream taking each junction into consideration.

Step 2 Enter in Col. 2 the tailwater elevation if the outlet will be submerged during the design storm otherwise refer to the tailwater discussion in 11.12.2 for procedure.

Step 3 Enter in Col. 3 the diameter (D_o) of the outflow pipe.

Step 4 Enter in Col. 4 the design discharge (Q_o) for the outflow pipe.

Step 5 Enter in Col. 5 the length, L_o, of the outflow pipe.

Step 6 Enter in Col. 6 the outlet velocity of flow, V_o.

Step 7 Enter in Col. 7 the velocity head, $V_o^2/2g$.

Step 8 Enter in Col. 8 the exit loss, H_o.

Step 9 Enter in Col. 9 the friction slope (SF_o) in m/m (ft/ft) of the outflow pipe. This can be determined by using the equation 11.21. Note: Assumes full flow conditions.

Step 10 Enter in Col. 10 the friction loss (H_f) which is computed by multiplying the length (L_o) in Col. 5 by the friction slope (SF_o) in Col 9. On curved alignments, calculate curve losses by using the formula $Hc = 0.0033\ (\Delta)(V_o^2/2g)$, where Δ = angle of curvature in degrees, and add to the friction loss.

Step 11 Enter in Col. 11 the initial head loss coefficient, K_o, based on relative structure size as computed by equation 11.26.

Step 12 Enter in Col. 12 the correction factor for pipe diameter, C_D, as computed by equation 11.27.

Step 13 Enter in Col. 13 the correction factor for flow depth, C_d, as computed by equation 11.28. Note this factor is only significant in cases where the d/D_o ratio is less than 3.2.

Step 14 Enter in Col. 14 the correction factor for relative flow, C_Q, as computed by equation 11.29.

Step 15 Enter in Col. 15 the correction factor for plunging flow, C_p, as computed by equation 11.30. The correction factor is only applied when $h>d$.

Step 16 Enter in Col. 16 the correction factor for benching, C_B, as determined in Table 11-9.

Step 17 Enter in Col. 17 the value of K as computed by equation 11.25.

Step 18 Enter in Col. 18 the value of the total manhole loss, $K\ (V_o^2/2g)$.

Step 19 If the tailwater submerges the outlet end of the pipe, enter in Col. 19 the sum of Col. 2 (TW elevation) and Col. 7 (velocity head) to get the EGL at the outlet end of the pipe. If the pipe is flowing full, but the tailwater is low, the EGL will be determined by adding the velocity head to $(d_c + D)/2$.

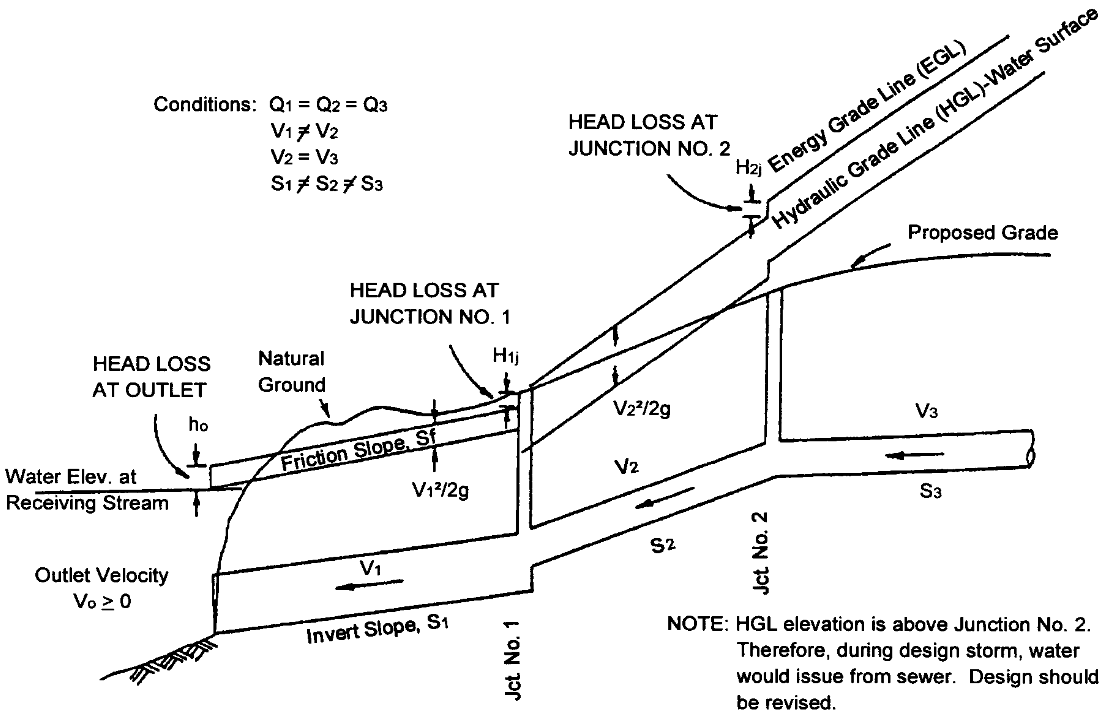
Step 20 Enter in Col. 20 the sum of the friction head (Col 10), the structure losses (Col 18), and the energy grade line (Col 19) at the outlet to obtain the EGL at the inlet end. This value becomes the EGL for the downstream end of the upstream pipe.

Step 21 Determine the HGL (Col 21) throughout the system by subtracting the velocity head (Col 7) from the EGL (Col 20).

Step 22 Check to make certain that the HGL is below the level of allowable high water at that point. If the HGL is above the finished grade elevation, water will exit the system at this point for the design flow.

The above procedure applies to pipes that are flowing full, as should be the condition for design of new systems. If a part full flow condition exists, the EGL is located one velocity head above the water surface.

IMPROPER DESIGN



PROPER DESIGN

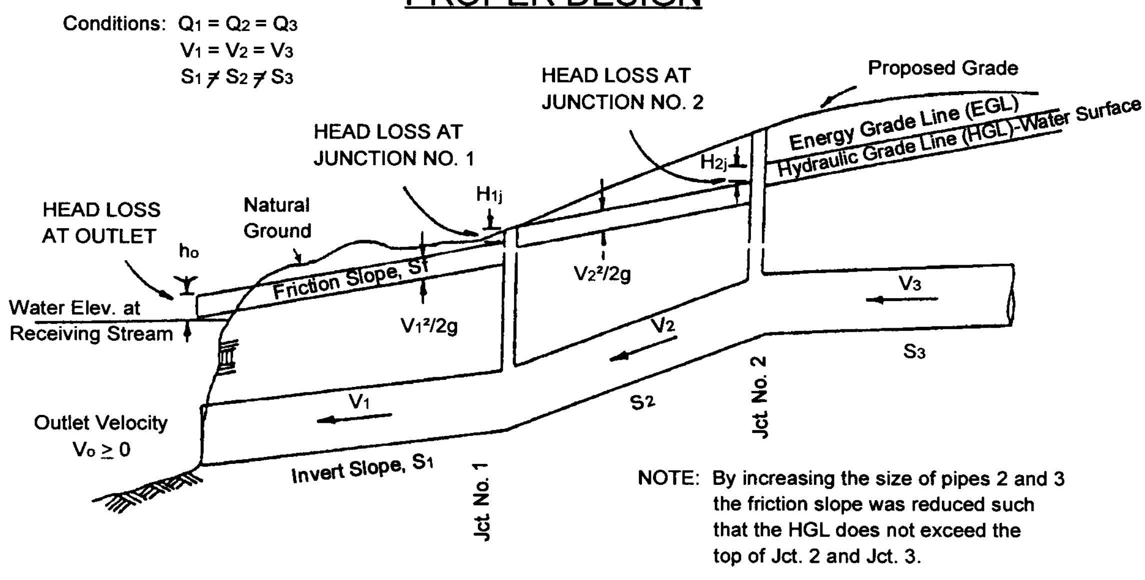


Figure 11-12 Use Of Energy Losses In Developing a Storm Drain System

Computed by _________ Date ________
Checked by __________ Date ________
Page ______ of ______

Project No. ______________________
Route ___________________________
Town ___________________________
Stations _________________________

Station	TW	D_0	Q_o	L_o	V_o	$V_o^2/2g$	H_o	SF_o	H_f	K_o	C_D	C_d	C_Q	C_p	C_B	K	$K(V_o^2/2g)$	EGL_0 2+7	EGL_i 10+18+19	HGL EGL-7	TOC Elev
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)

Table 11-10 Hydraulic Grade Line Computation Form