# Modeling Hydraulic and Energy Gradients in Storm Sewers: A Comparison of Computational Methods

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# Abstract

There are many engineering design programs capable of calculating the Hydraulic Gradient Line (HGL) and the Energy Gradient Line (EGL) for storm sewer pipe systems. Two of these software packages, UD-Sewer and StormCAD, perform the same functions. Both programs are capable of calculating the HGL and EGL, and both calculate the inflow for an urban basin. However, because the two packages use different equations, procedures and methods, they often yield slightly different results.

While UD-Sewer is the preferred hydraulic software package of the Urban Drainage and Flood Control District (UDFCD), some municipalities in the Denver Metropolitan area accept both software packages for the calculation of HGL/EGL for storm sewers. This use of multiple design programs can cause engineering inconsistencies and difficulties in reviewing submittals. AMEC understands that this is a problem for the local engineering community and has performed a detailed study in order to propose a solution.

This study compared the HGL/EGL calculation results of UD-Sewer and StormCAD and assessed their differences. A number of test cases were created for this study in order to perform sensitivity analyses. The results of this study and sensitivity analyses were used to create engineering guidelines to be used to resolve inconsistencies.

# Acknowledgements

UD-sewer and StormCAD have both been used for storm sewer system design in the Denver Metro area for many years. The inconsistency in results has become a challenge in the engineering community. AMEC appreciated this opportunity to serve our engineering community by completing this research study.

We would like to acknowledge the help and support in the preparation of this report of Quang H. Nguyen, P.E., CFM SEMSWA CIP manager by performing the testing model review. The Urban Drainage and Flood Control District partially funded this study. We would also like to acknowledge the comments and support from the City and County of Denver and the City of Aurora.

# 1. Introduction

With the introduction of sophisticated computerized storm sewer design methods, traditional designs based on hand calculations are not frequently used in engineering practice. Two of the most commonly used hydraulic software packages in the Denver area are UD-Sewer and StormCAD.

The use of multiple hydraulic software packages causes inconsistencies. These inconsistencies can be a function of different algorithms used within the coding of the models, different methodologies used to calculate major and minor losses, and different boundary conditions between the two models. **Figure 1** shows an example of these inconsistencies when comparing UD-Sewer and StormCAD.

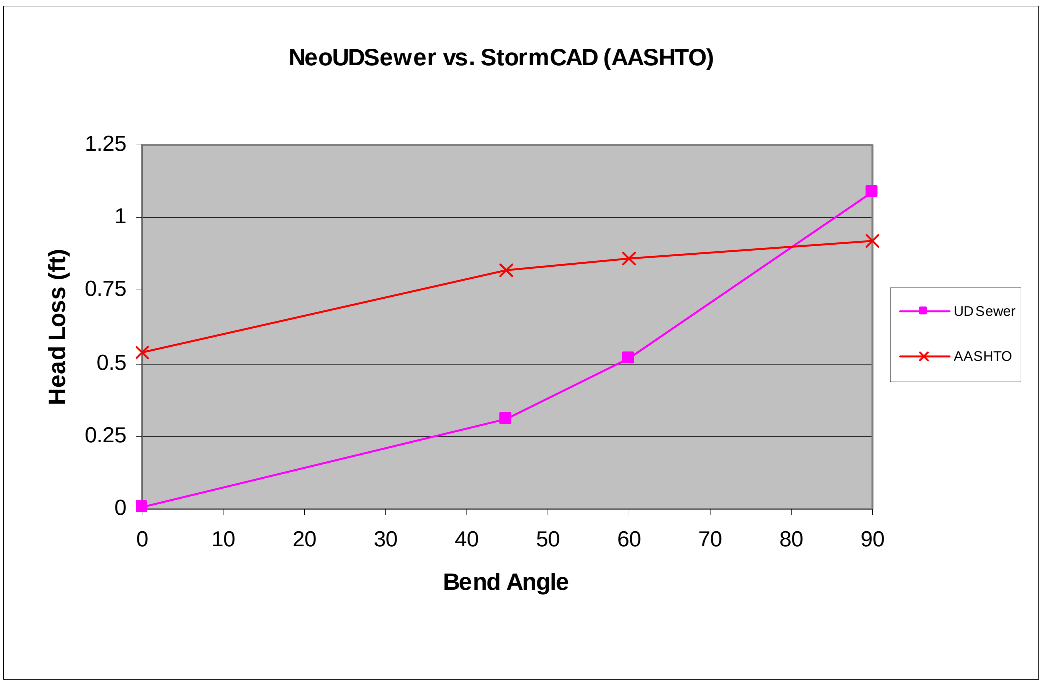



**Figure 1 –** Head loss results as a function of bend angle for UD-Sewer and StormCAD

Storm sewers have both conveyance and junction losses that can affect the HGL and EGL in both programs. Pipe loss methods for both programs are similar, while junction loss methods are not. Some municipalities suggest using example 6.13 in the UDFCD Manual (Chapter 6, Streets Inlets Storm Sewers) as a “check” if the engineer uses StormCAD instead of UD-Sewer. The goal of this model calibration is to verify that the loss coefficients and other system assumptions used in the StormCAD model are equivalent to the methodology applied by UD-Sewer. This “check” can be time consuming and troublesome if results differ.

The hydraulic design of storm sewer systems is based on energy conservation and mass continuity equations. Conservation of energy consists of two different types of head losses – pipe losses and junction losses. Pipe losses are major losses within the sewer pipes and junction losses occur at inlets, manholes, junction boxes, etc. Junctions in storm sewer systems are normally used as stormwater collection structures, connections between two or more pipes, and/or grade and alignment changes.

Storm sewer pipe hydraulics have been extensively studied and numerous lab testing results have been published. These lab tests and their results help engineers understand stormwater flow energy losses. However, the focus of this study was to reduce engineering analysis inconsistencies between StormCAD and UD-Sewer HGL calculations. The goal of this study, therefore, was not in measuring the accuracy of the HGL analyses, but in comparing the inconsistencies of the two programs.

## 2. Purpose and Project Scope

The purpose of this study was to compare the HGL calculation results of UD-Sewer and StormCAD hydraulic software packages and their abilities to predict major and minor storm sewer losses. The scope included:

- Classifying the storm sewer system energy losses for both UD-Sewer and StormCAD
- Generating the difference in energy losses through the numerical testing of UD-Sewer and StormCAD
- Providing an engineering analysis and comparison of the energy losses between UD-Sewer and StormCAD
- Providing an engineering guideline for StormCAD so that in can be depended upon to produce similar and more conservative results than UD-Sewer.

Major and minor losses within a given storm sewer system can vary significantly if multiple methodologies are used in both conditions. Evaluating these differences can provide us with a tool that will allow the engineer to be confident in the accuracy of the hydraulic output of his/her choosing.

## 3. Background of Stormwater System Energy Loss

The water surface profile represents the hydraulic gradient line in a sewer line. The difference between the hydraulic gradient line and its energy gradient line is the flow kinetic energy, or velocity head (Guo). The largest losses in a storm sewer system are friction losses. They are directly related to the velocity in the pipe – meaning the higher the velocity, the greater the friction loss, and vice versa. By applying the energy principle to both the conveyance elements and to junction elements of any storm sewer system, the engineer can quantify the energy losses associated with conveyances and junctions (manholes, inlets, etc).

### 3.1 Pipe Losses

Energy principles are used for both UD-Sewer and StormCAD to determine the headloss as a result of pipe flow using the Bernoulli energy equation. Because storm sewer pipe losses correspond linearly to pipe length, both programs can use Manning's friction to determine the headloss associated with a given length. Friction losses in steady, uniform flow can be estimated using **Equation 1**.

$$H_f = \overline{S_f} \cdot X \qquad \text{Equation (1)}$$

where, $H_f$ = friction losses

$S_f$ = friction slope

$X$ = distance between Sections *a* and *b*

Friction loss is the friction head or loss per unit length of channel or conduit. For uniform flow the friction slope coincides with the energy gradient, but where a distinction is made between energy losses due to bends, expansions, impacts, etc., a distinction must also be made between the friction slope and the energy gradient. The friction slope is equal to the bed or surface slope only for uniform flow in uniform open channels.

Four conditions were considered for pipe loss comparisons between StormCAD and UD-Sewer:

- Subcritical Flow with Unsubmerged Exit
- Supercritical Flow with Unsubmerged Exit
- Subcritical Flow with Submerged Exit
- Supercritical Flow with Submerged Exit

**Figures 2, 3, 4 and 5** represent the comparison of UD-Sewer and StormCAD runs as a function of pipe loss. The test condition for supercritical flow with an unsubmerged exit was a 0.5% slope, 70 cfs, and 42" RCP with a free discharge exit. The test condition for subcritical flow with an unsubmerged exit was a 1.0% slope, 70 cfs, and 42" RCP with a free discharge exit. The test condition for subcritical flow with a submerged exit was a 0.5% slope, 70 cfs, and 42" RCP with a three foot tailwater condition. The test condition for supercritical flow with a submerged exit was a 1.0% slope, 70 cfs, and 42" RCP with a three foot tailwater condition.

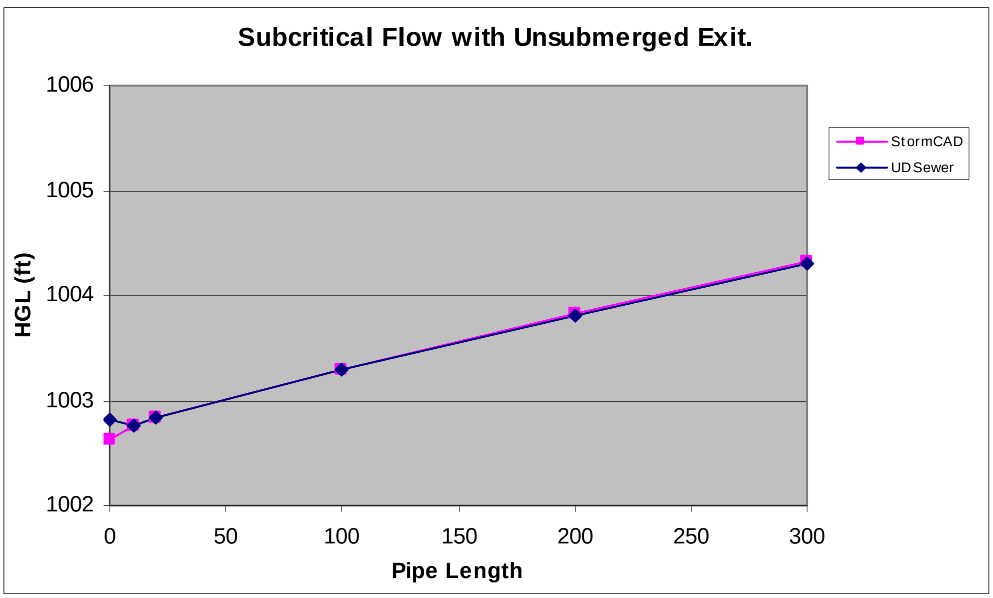



**Figure 2 -** Subcritical Flow with Unsubmerged Exit

**Figure 2** shows that subcritical flow with an unsubmerged exit condition was applied to both UD-Sewer and StormCAD models. Both models converge within a relatively short length of pipe and calculate the same HGL for the entire length of pipe (300 ft) after convergence. Both models converge to steady state uniform flow after 100 ft. The difference between UD-Sewer and StormCAD for the subcritical flow with an unsubmerged exit condition is that UD-Sewer has a downstream boundary condition of normal depth, while StormCAD has a downstream boundary condition of critical depth.

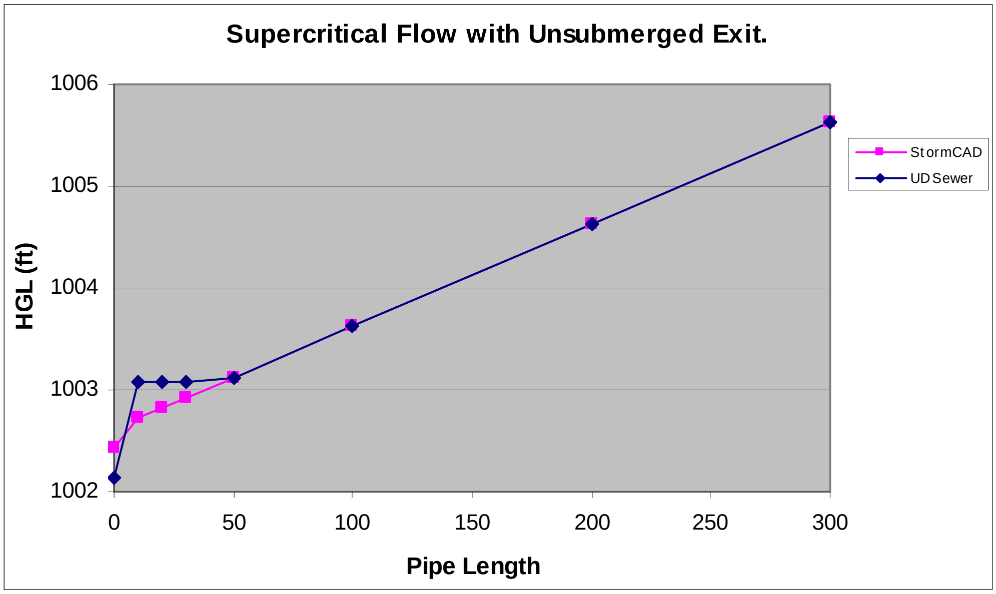



**Figure 3 -** Supercritical Flow with Unsubmerged Exit

As shown in **Figure 3,** supercritical flow with an unsubmerged exit condition was applied to both UD-Sewer and StormCAD models. Both models converge to critical depth within 50 feet of pipe and predict the same HGL for the entire length of pipe (300 ft) after convergence. Both programs predict an S2 curve to converge to critical depth. The difference between Neo UD-Sewer and StormCAD for the supercritical flow with an unsubmerged exit condition is that Neo UD-Sewer has a downstream boundary condition of normal depth, while StormCAD has a downstream boundary condition between normal depth and critical depth.

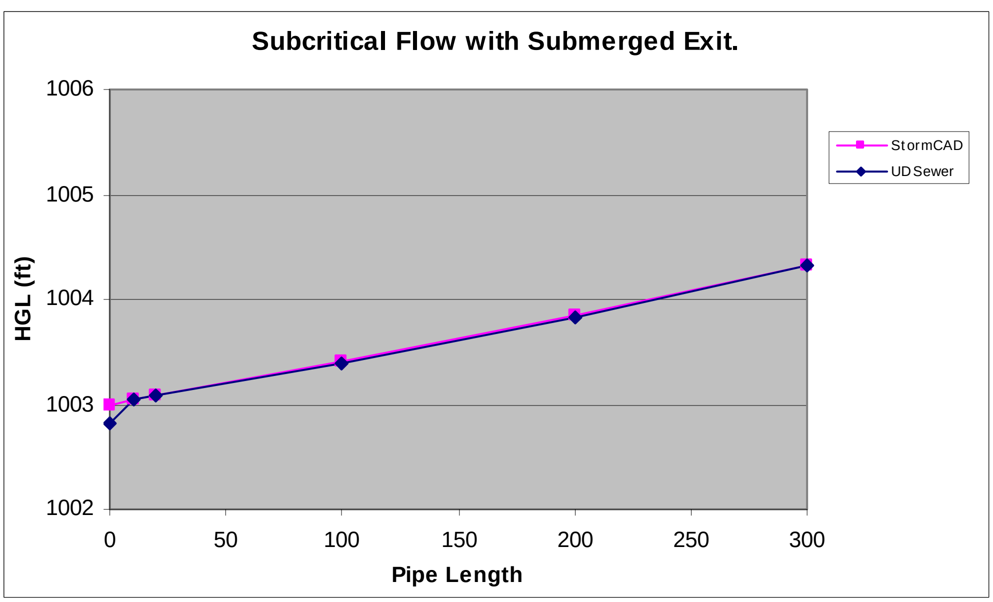



**Figure 4 -** Subcritical Flow with Submerged Exit

**Figure 4** shows that subcritical flow with a submerged exit condition was applied to both UD-Sewer and StormCAD models. Both models converge to steady state within a relatively short length of pipe and predict the same HGL for the entire length of pipe (300 ft) after convergence. The difference between UD-Sewer and StormCAD for the subcritical flow with a submerged exit condition is that UD-Sewer has a downstream boundary condition of normal depth, while StormCAD has a downstream boundary condition of tailwater depth.

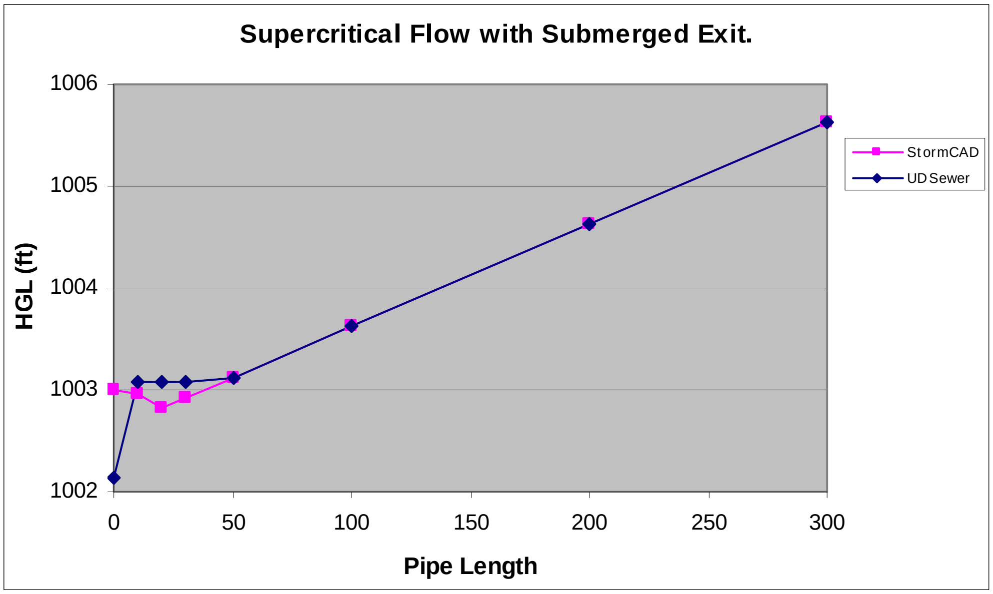



**Figure 5 -** Supercritical Flow with Submerged Exit

As shown in **Figure 5,** supercritical flow with a submerged exit condition was applied to both UD-Sewer and StormCAD models. Both models converge to critical depth within 50 feet and predict the same HGL for the entire length of pipe (300 ft) after convergence. UD-Sewer has a downstream boundary condition of normal depth before converging to tailwater condition, while StormCAD has a tail water depth as its initial condition followed by a hydraulic jump then converting to an S2 curve before converging on critical depth.

## 3.2 Junction Losses

The total energy head losses at junctions are determined for inlets, manholes and/or bends in the design of storm sewer systems that can consist of multiple laterals with one exit at every junction. The basic equations for junction losses where there are significant upstream and downstream velocities are assumed to be a function of flow velocity. The hydraulic analysis through a manhole focuses on the calculation of the energy loss from the inflow pipes to the outflow pipe. Several determining factors affect the computation of the energy loss coefficient in the HGL methodology; these include the manhole size relative to the outlet pipe diameter, the depth of flow in the manhole, the amount of discharge, the inflow pipe angle, the plunge height, the relative pipe diameter, and the floor configuration.

### 3.2.1 UD-Sewer

UD-Sewer hydraulic functions use an energy analysis across each junction that consists of two types of junction losses:

- Bend losses – are caused by change in flow direction as a result of change in sewer alignment
- Lateral losses – caused by incoming lateral sewers that produce additional losses to the trunk line.

Friction loss as a function of flow length is considered negligible across all junctions, so the headloss between the entrance of the junction and the exit is Bend losses + Lateral Losses for the trunk line (Guo, 2006). The lateral line only uses bend loss in its headloss calculations. **Figures 7 through 15** present a comparison of UD-Sewer junction losses to four junction loss methods of StormCAD.

### 3.2.1.1 Bend Losses

An energy loss caused by stormwater flow changing direction at a junction is known as bend loss. Bend loss is often estimated as a fraction of the full flow velocity head in the incoming sewer. The UD-Sewer bend loss equation is as follows:

$$E_1 = E_4 + H_b \qquad \textit{Equation (2)}$$

$$H_b = K_b \frac{V_f^2}{2g} \qquad \textit{Equation (3)}$$

where, $H_b$ = Bend loss

$V_f$ = full flow velocity in the sewer coming to the manhole

$K_b$ = Bend loss coefficient

The value of $K_b$ is determined by the angle between the incoming flow direction and the outgoing flow direction at the manhole. The value of $K_b$ ranges from 0.05 to 1.32 (for non-shaped manholes) depending on the incoming and outgoing flow directions (Guo).

### 3.2.1.2 Lateral Loss

The energy loss that occurs as a result of two stormwater flows meeting at a junction is known as a lateral loss. Lateral losses are only applicable to the trunk line sewers. Lateral losses account for the additional turbulence caused by the branch sewers. The value of lateral loss coefficient, $K_m$, is determined by the angle between the branch line and the main line. UD-Sewer lateral loss equation is as follows:

$$E_1 = E_4 + H_b + H_m \qquad \textit{Equation (4)}$$

$$H_m = \frac{V_{fo}^2}{2g} - K_m \frac{V_{fi}^2}{2g} \qquad \textit{Equation (5)}$$

where, $H_b$ = Bend loss

$H_m$ = Lateral loss

$V_{fo}$ = full flow velocity of the outgoing sewer at manhole,

$V_{fi}$ = full flow velocity of incoming lateral at manhole

$K_m$ = Lateral loss coefficient

The value of $K_m$ ranges from 0.25 to 0.75 (for non-shaped manholes) depending on the incoming and outgoing flow directions (Guo).

### 3.2.2 StormCAD

StormCAD has five different methods of determining junction headloss: HEC-22 Energy, Standard, Generic, Absolute and AASHTO. The Absolute method allows the user to define the junction headloss using an outside calculation, and so this study only focused on HEC-22 Energy, Standard, Generic, and AASHTO methods to be compared to UD-Sewer results. These four headloss methods are calculations that StormCAD produces which can be directly compared to UD-Sewer.

#### 3.2.2.1 HEC-22 Energy Method

The HEC-22 Energy method (from the FHWA's Urban Drainage Design Manual, Hydraulic Engineering Circular No. 22) links headloss to velocity head by multiplying it by an adjusted headloss coefficient. The adjusted headloss coefficient is approximated using an initial headloss coefficient, correction factor for pipe diameter (pressure flow only), correction factor for flow depth, correction for relative flow, correction for plunging flow and correction for benching.

$$h_s = K\frac{V_0^2}{2g}$$ *Equation (6)*

$$\mathrm{K} = \mathrm{K}_0\mathrm{C}_\mathrm{D}\mathrm{C}_\mathrm{d}\mathrm{C}_\mathrm{Q}\mathrm{C}_\mathrm{p}\mathrm{C}_\mathrm{B}$$ *Equation (7)*

where: K = Adjusted headloss coefficient

$K_0$ = Initial headloss coefficient based on relative junction size

$C_D$ = Correction factor for the pipe diameter

$C_d$ = Correction factor for flow depth

$C_Q$ = Correction for relative flow

$C_p$ = Correction for plunging flow

$C_B$ = Correction factor for benching

#### 3.2.2.2 Standard Method

The Standard method links headloss to the pipe's exit velocity by multiplying a headloss coefficient by the exit velocity head. The coefficient is approximated using typical headloss coefficients.

$$h_s = K\frac{V_0^2}{2g}$$ *Equation (8)*

where: $h_s$ = Structure headloss (ft,m)

$V_0$ =Exit pipe velocity (ft/s, m/s)

g = Gravitational acceleration constant (ft/s$^2$, m/s$^2$)

K = Headloss coefficient (unitless)

#### 3.2.2.3 Generic Method

The Generic method computes junction headloss by multiplying downstream and upstream velocity heads by user defined downstream and upstream coefficients and then subtracting the resulting upstream from the downstream.

$$h_s = K_o \cdot \frac{V_o^2}{2g} - K_1 \cdot \frac{V_1^2}{2g}$$ *Equation (9)*

where, $h_s$ = Structure headloss (ft, m)

$V_o$ = Exit pipe velocity (ft/s, m/s)

$K_o$ = Downstream coefficient (unitless)

$V_1$ = Governing upstream pipe velocity (ft/s, m/s)

$K_1$ = Upstream coefficient (unitless)

g = Gravitational acceleration constant (ft/s$^2$, m/s$^2$)

#### 3.2.2.4 AASHTO Method

The AASHTO method (from the AASHTO Model Drainage Manual) computes using power-loss methods. Head losses (Contraction Loss, Bend Loss, and Expansion Loss) are summed and then multiplied by correction factors for non-piped flow and for shaping.

$$h_s = (h_c + h_b + h_e) \cdot C_n \cdot C_s$$ *Equation (10)*

where: $h_s$ = Structure headloss (m, ft)

$h_c$ = Contraction loss (m, ft)

$h_b$ = Bend loss (m, ft)

$h_e$ = Expansion loss (m, ft)

$C_n$ = Correction factor for non-piped flow (unitless)

$C_s$ = Correction factor for shaping (unitless)

# 4. Modeling Variables and Criteria

As **Table 1** shows, seven types of junctions with three flow regimes were used as modeling scenarios in this study to characterize headloss for UD-Sewer and StormCAD. All seven junction types had all three flow regimes (subcritical, supercritical, and surcharged) applied in both UD-Sewer and StormCAD models. Junctions were all considered to be non-shaped with appropriate loss coefficients applied. Pipe scenario friction methods were all set to use Manning's equation for all StormCAD runs and UD-Sewer (Manning's default friction method).

## 4.1 Bend Angles and Lateral Lines

Multiple bend angles and lateral line angles were used to characterize head loss for both UD-Sewer and StormCAD. **Table 1** shows the bend angles and lateral angles used in this study.

**Table 1 -** Bend Angle and Lateral Angle Variables

<table>
<tr><td rowspan="5">Bend Loss</td><td colspan="2">Bend Angle</td></tr>
<tr><td colspan="2">0º</td></tr>
<tr><td colspan="2">45º</td></tr>
<tr><td colspan="2">60º</td></tr>
<tr><td colspan="2">90º</td></tr>
<tr><td rowspan="5">Lateral Loss</td><td colspan="2">One Lateral</td></tr>
<tr><td>Mainline</td><td>Lateral</td></tr>
<tr><td>0º</td><td>45º</td></tr>
<tr><td>0º</td><td>60º</td></tr>
<tr><td>0º</td><td>90º</td></tr>
</table>

### 4.2 Slope

Multiple slopes were used in this study to force multiple flow regimes. The flow regimes that were used are subcritical flow and supercritical flow.

### 4.3 Subcritical

Subcritical flow is a flow state where the role played by gravity forces is more pronounced; so the flow has a low velocity and is often described as tranquil and streaming (Chow). Subcritical flow regime was used as a variable within all test cases.

### 4.4 Supercritical

Supercritical flow is a flow state where inertial forces become dominant; so the flow has a high velocity and is usually described as rapid, shooting, and torrential (Chow). Supercritical flow regime was used as a variable within all test cases.

### 4.5 Discharge

Multiple discharges were used in this study to force steady state uniform flow and surcharged conditions.

### 4.6 Surcharged

Surcharging refers to pipes running full or part-full, conveying flow under pressure. Surcharged flow was used as a variable within all test cases.

### 4.7 Pipe Size

Multiple pipe sizes were used in this analysis to determine the effects on junction losses due to varying pipe sizes.

# 5. Test Case Results

## 5.1 Bend Loss

**Figures 6 through 8** show bend loss as a function of differing pipe angles for multiple modeling variables. Bend loss variables are supercritical flow, subcritical flow, and surcharge flow regimes.

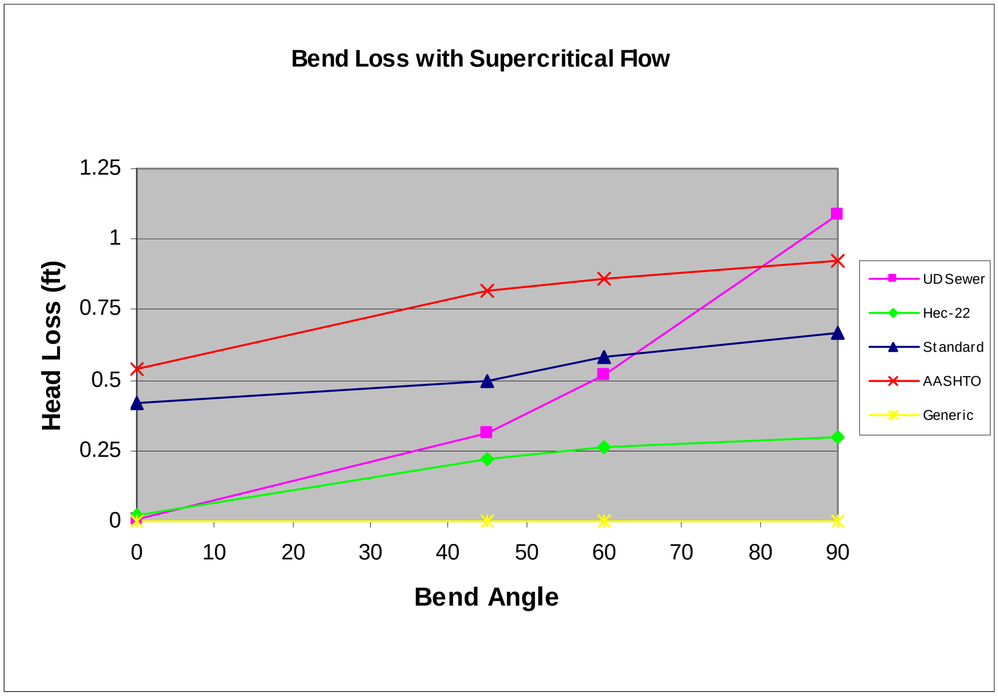



**Figure 6 -** Bend Loss with Supercritical Flow

**Figure 6** shows bend loss as a function of bend angle for the four StormCAD methods (HEC-22 Energy, Standard, Generic, and AASHTO methods) and the UD-Sewer model. Bend loss with supercritical flow was analyzed using the following variables: slope of 1.0%, pipe size of 42" RCP, and a discharge of 70 cfs. Standard method compares favorably to UD-Sewer in all cases except for the 90˚ where UD-Sewer has a higher headloss. **Equations 3 and 8** show that the Standard method from StormCAD and the UD-Sewer model have identical bend loss equations with the only difference being differing bend loss coefficients. All headloss methods use full flow velocities in their head loss calculations.

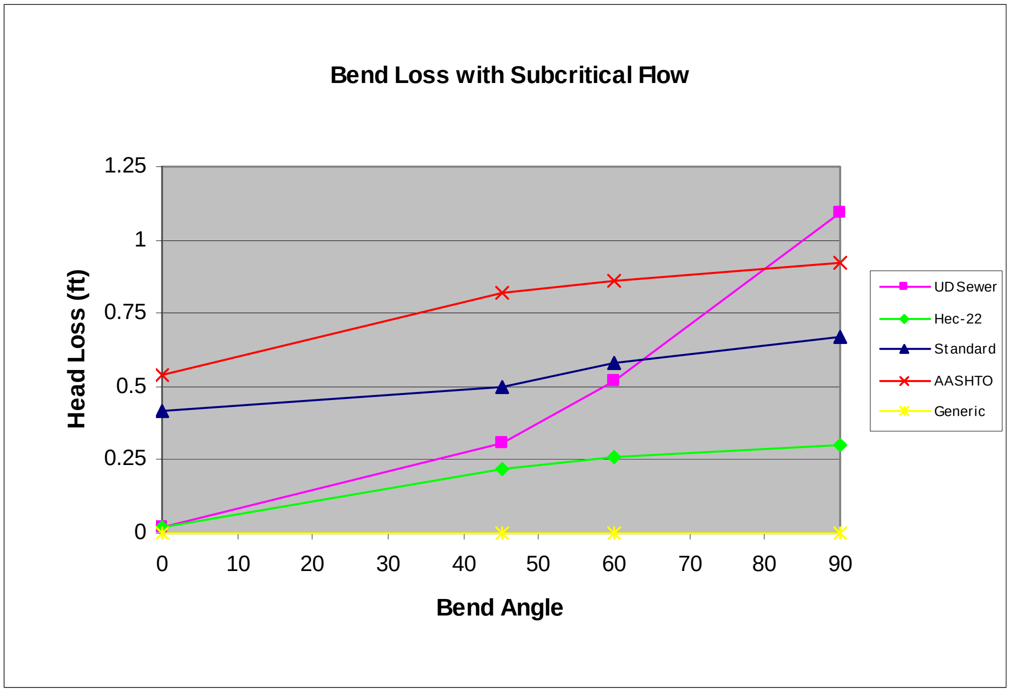



**Figure 7 -** Bend Loss with Subcritical Flow

**Figure 7** shows bend loss as a function of bend angle for the four StormCAD methods (HEC-22 Energy, Standard, Generic, and AASHTO methods) and the UD-Sewer model. Bend loss with subcritical flow was analyzed using the following variables: slope of 0.5%, pipe size of 42" RCP, and a discharge of 70 cfs. Standard method compares favorably to UD-Sewer in all cases except for the 90˚ where UD-Sewer has a higher headloss. All headloss methods use full flow velocities in their head loss calculations so there is no difference between the supercritical and subcritical runs. **Equations 3 and 8** show that the Standard method from StormCAD and the UD-Sewer model have identical bend loss equations with the only difference being differing bend loss coefficients. All headloss methods use full flow velocities in their head loss calculations. It should be noted that using momentum principles, the head loss for supercritical flow through a junction, is greater than that of subcritical flow.

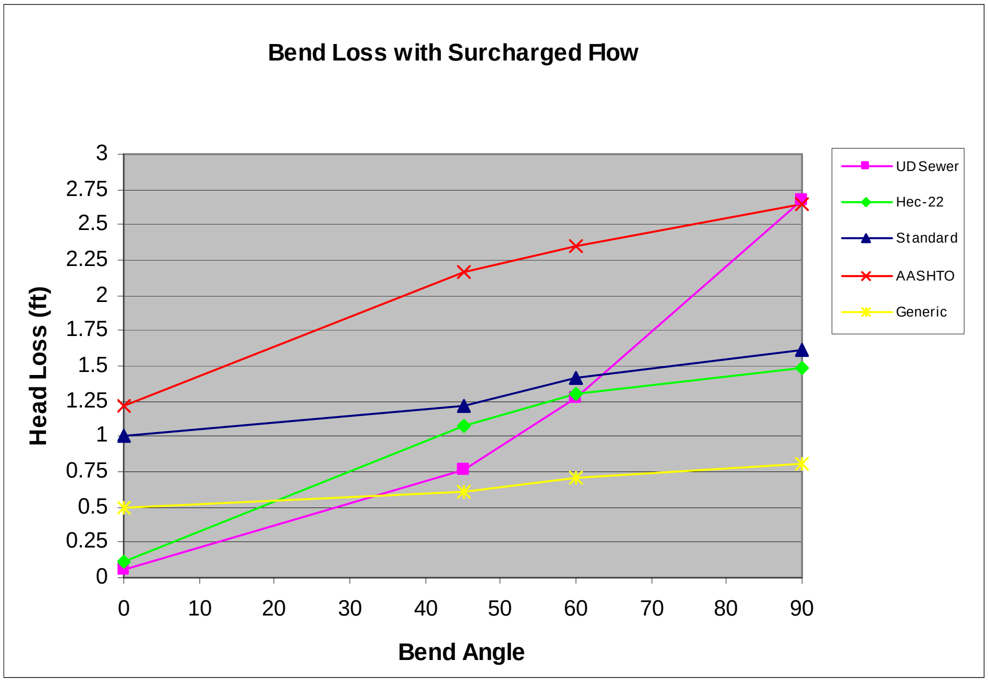



**Figure 8 -** Bend Loss with Surcharged Flow

**Figure 8** shows bend loss as a function of bend angle for the four StormCAD methods (HEC-22 Energy, Standard, Generic, and AASHTO methods) and the UD-Sewer model. Bend loss with supercritical flow and surcharged was analyzed using the following variables: slope of 1.0%, pipe size of 42" RCP, and a discharge of 110 cfs. Standard method compares favorably to UD-Sewer in all cases except for the 90˚ where UD-Sewer has a higher headloss. All headloss methods use V=Q/A velocities in their head loss calculations. **Equations 3 and 8** show that the Standard method from StormCAD and the UD-Sewer model have identical bend loss equations with the only difference being differing bend loss coefficients.

## 5.2 Combined Loss (Bend and Lateral Loss)

**Figures 9 through 12** show combined loss as a function differing pipe angles for multiple modeling variables. Combined loss variables are supercritical flow, subcritical flow, multiple laterals, and surcharge flow regimes. Lateral loss within StormCAD cannot be quantified as a stand alone loss.

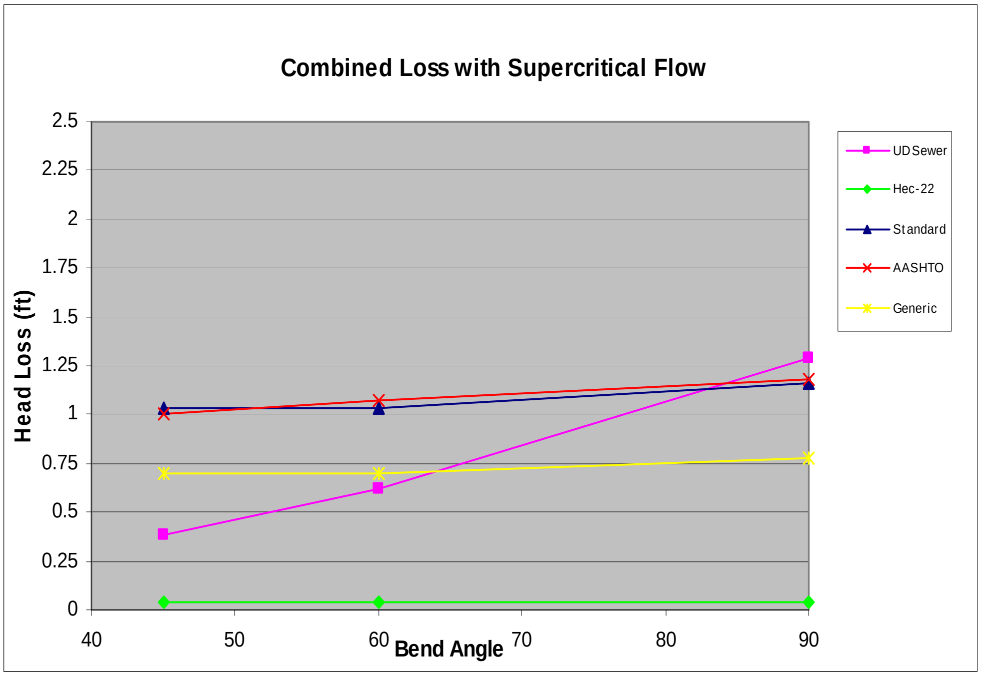



**Figure 9 -** Combined Loss with Supercritical Flow

**Figure 9** shows combined loss as a function of bend angle of the lateral line for the four StormCAD methods (HEC-22 Energy, Standard, Generic, and AASHTO methods) and the UD-Sewer model. Combined loss with supercritical flow was analyzed using the following variables: slope of 1.0%, main line pipe size of 42” RCP, lateral line pipe size of 42” RCP, and a discharge of 70 cfs. Standard method compares favorably and conservatively to UD-Sewer in all cases. UD-Sewer and the Standard Method use full flow velocities in their lateral loss calculations where HEC-22 Energy, AASHTO, and Generic methods do not.

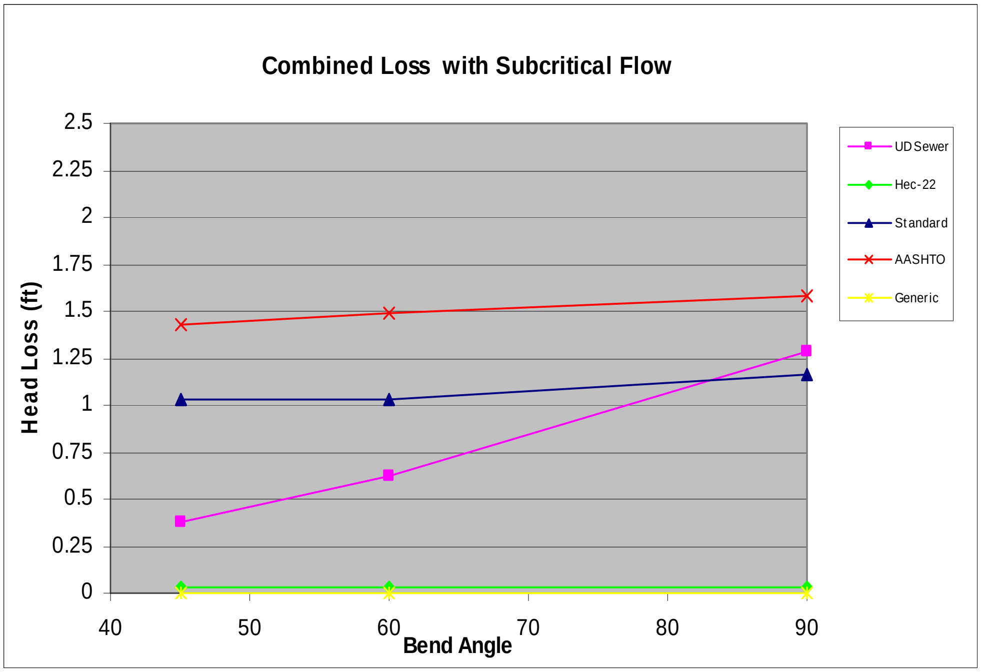



**Figure 10 –** Combined Loss with Subcritical Flow

**Figure 10** shows combined loss as a function of bend angle of the lateral line for the four StormCAD methods (HEC-22 Energy, Standard, Generic, and AASHTO methods) and the UD-Sewer model. Combined loss with subcritical flow was analyzed using the following variables: slope of 0.5%, main line pipe size of 42" RCP, lateral line pipe size of 42" RCP, and a discharge of 70 cfs. Standard method compares favorably and conservatively to UD-Sewer in all cases. UD-Sewer and the Standard Method use full flow velocities in their lateral loss calculations where HEC-22 Energy, AASHTO, and Generic methods do not.

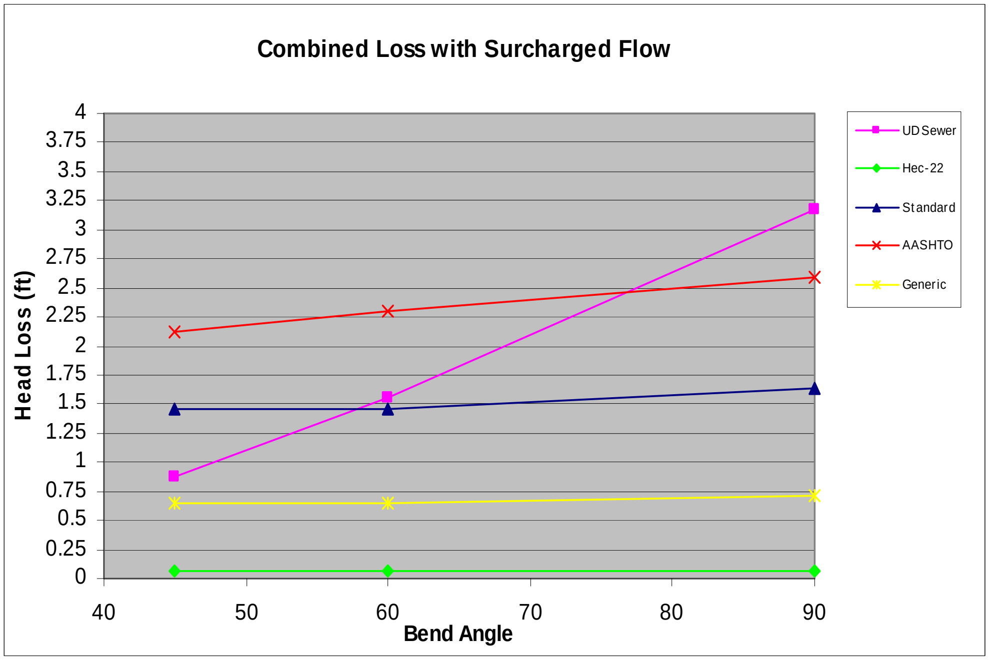



**Figure 11 –** Combined Loss with Surcharged Flow

**Figure 11** shows combined loss as a function of bend angle of the lateral line for the four StormCAD methods (HEC-22 Energy, Standard, Generic, and AASHTO methods) and the UD-Sewer model. Combined loss with a surcharged supercritical flow regime was analyzed using the following variables: slope of 1.0%, main line pipe size of 42" RCP, lateral line pipe size of 42" RCP, and a discharge of 110 cfs. Standard method compares favorably and to UD-Sewer in all cases. All headloss methods use V=Q/A velocities in their head loss calculations.

# 6. Engineering Analysis and Conversion Table

After comparing all StormCAD headloss methods as a function of each variable (supercritical, subcritical, surcharged, bend loss, and lateral loss), the results of this study show that StormCAD's **Standard Method** for calculating headloss most closely resembled UD-Sewer's headloss results.

Furthermore, the same bend loss equation is used in both UD-Sewer and StormCAD's Standard Method, thus giving a direct comparison between the two. The results also show that there are differing results between the two models (downstream boundary conditions, differing headloss, etc). The user defined K value for the standard method also provides the engineer with the option of entering the conversion coefficients thus giving StormCAD similar results to UD-Sewer.

An analytical analysis approach was taken to derive a K coefficient to use in the StormCAD model that would produce the same or greater headloss achieved with UD-Sewer (given the same input). The analytical approach was to set the UD-Sewer junction loss (Equation 11) equal to the Standard Method junction loss (Equation 12). Using the product from the experimental data, this results in one unknown combined junction loss equation (Equation 13). Below are the equations used to derive a K coefficient that can be used in StormCAD to replicate Neo-UDSewer results:

## 6.1 UD-Sewer Junction Loss

$$H_j = k_{bT} \cdot \left(\frac{V_{fT}^2}{2g}\right) + \left[\left(\frac{V_{fo}^2}{2g}\right) - k_m \cdot \left(\frac{V_{fi}^2}{2g}\right)\right] + k_{bL} \cdot \left(\frac{V_{fi}^2}{2g}\right)$$ *Equation (11)*

where, $Hj$ = UD-Sewer junction loss

$k_{bT}$ = Bend loss coefficient at truckling

$k_{bL}$ = Bend loss coefficient at lateral

$V_{fT}$ = full flow velocity of trunk line at manhole

$V_{fi}$ = full flow velocity of incoming lateral at manhole

$k_m$ = Lateral loss coefficient

$V_{fo}$ = full flow velocity of the outgoing sewer at manhole

## 6.2 Standard Method Junction Loss

$$H_s = k \cdot \frac{V_o^2}{2g}$$ *Equation (12)*

where, $Hs$ = Standard method junction loss

$Vo$ = Full flow exit velocity at manhole

$k$ = Head Loss Coefficient

$g$ = Acceleration due to Gravity

## 6.3 Combined Junction Loss Equation

$$H_j = H_s = k_{bT} \cdot \left( \frac{V_{fT}^2}{2g} \right) + \left[ \left( \frac{V_{fo}^2}{2g} \right) - k_m \cdot \left( \frac{V_{fi}^2}{2g} \right) \right] + k_{bL} \cdot \left( \frac{V_{fi}^2}{2g} \right) = k \cdot \left( \frac{V_o^2}{2g} \right) \qquad \textit{Equation (13)}$$

where, *Hj* = UD-Sewer junction loss

*Hs* = Standard method junction loss

$k_{bT}$ = Bend loss coefficient at truckling

$k_{bL}$ = Bend loss coefficient at lateral

$V_{fT}$ = Full flow velocity of trunk line at manhole

$V_{fi}$ = Full flow velocity of incoming lateral at manhole

*Vo* = Full flow velocity of trunk line at manhole

*k* = Head Loss Coefficient

*g* = Acceleration due to Gravity

**Table 2 -** StormCAD Standard Method Conversions

| StormCAD Conversion Table | | | |
|---|---|---|---|
| Bend Loss | Bend Angle | K coefficient Conversion | |
| | 0 | 0.05 | |
| | 22.5 | 0.1 | |
| | 45 | 0.4 | |
| | 60 | 0.64 | |
| | 90 | 1.32 | |
| Lateral Loss | 1 Lateral K coefficient Conversion | | |
| | Bend Angle | Non Surcharged | Surcharged |
| | 45 | 0.27 | 0.47 |
| | 60 | 0.52 | 0.9 |
| | 90 | 1.02 | 1.77 |
| | 2 Laterals K coefficient Conversion | | |
| | 45 | 0.96 | |
| | 60 | 1.16 | |
| | 90 | 1.52 | |

The engineering guidelines from this study provide the methodology needed to reach an HGL analysis result using StormCAD which replicates that of UD-Sewer. However, the following limitations apply:

- The full pipe velocity should not exceed 18 fps
- The conversion only applies for the storm sewer pipe sizes 42” or less
- A regional storm sewer system should use UD-Sewer only

## 6.4 Case Example

An example was created for this study to show how to replicate UD-Sewer results using the StormCAD standard method. The example shows a storm sewer system with a 300 ft pipe length, 1% slope and 70 cfs discharge. The storm sewer pipe bends at a junction at a 90° angle (**Figure 12**).

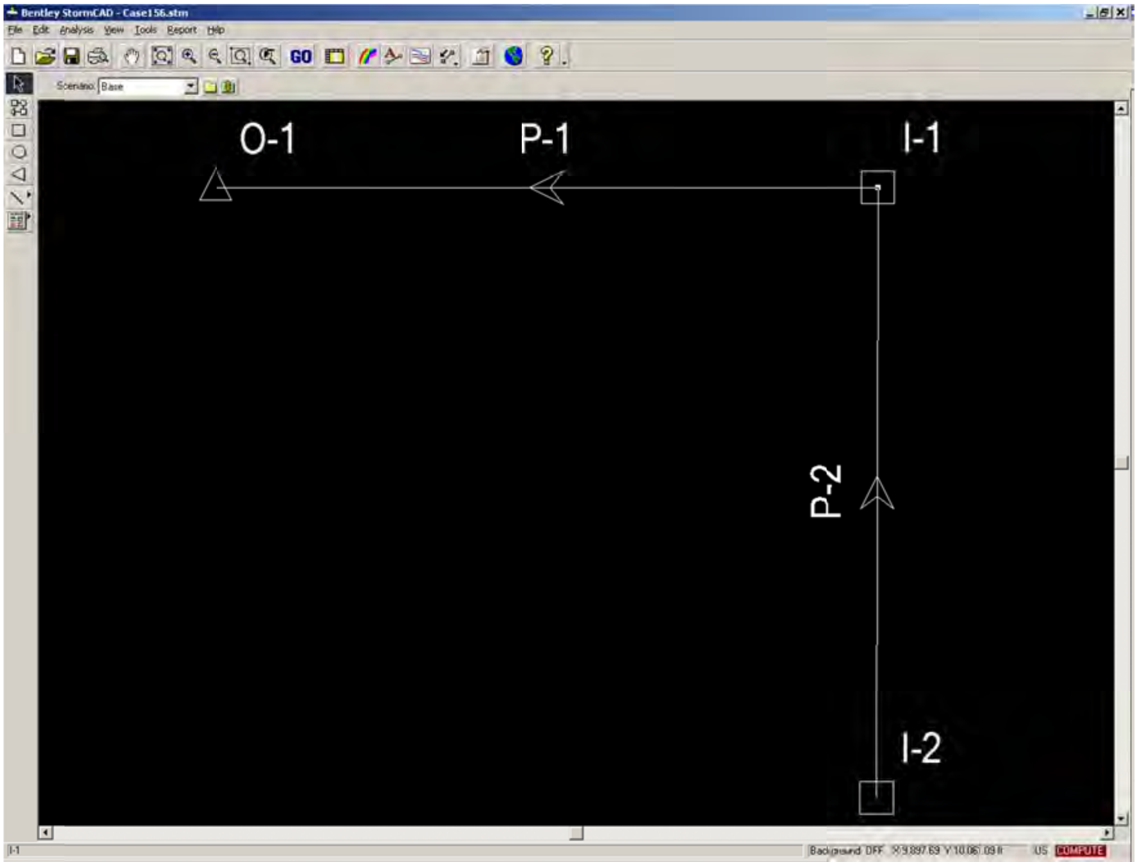



**Figure 12 -** Screenshot from StormCAD, this storm sewer system has 2 pipes that link at the I-1 Junction and bend 90 degrees. At the Junction point, double click to enter edit mode.

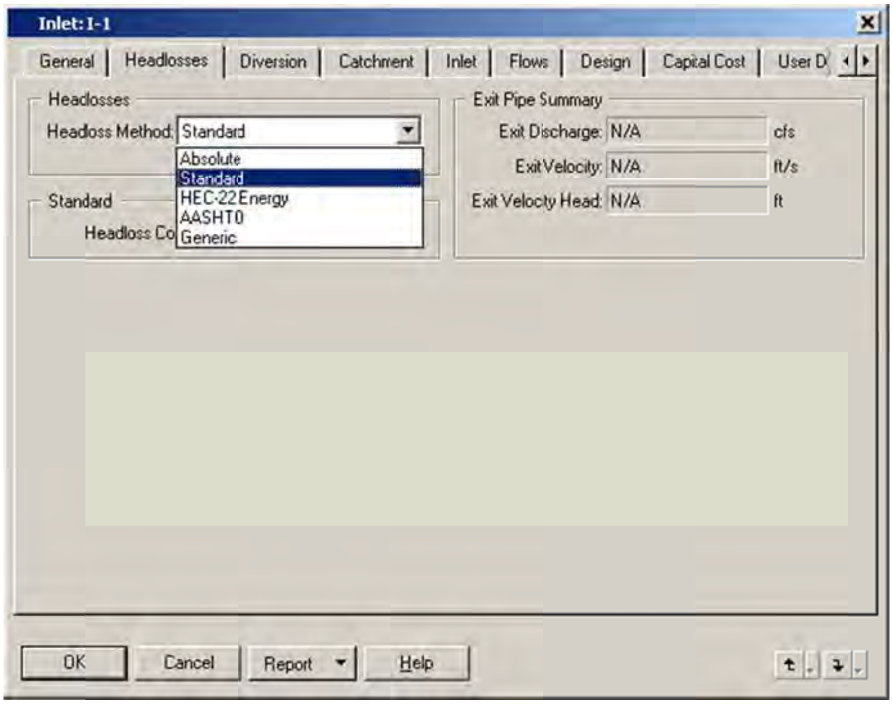



**Figure 13 -** Under the headloss tab select "Standard" as the headloss method

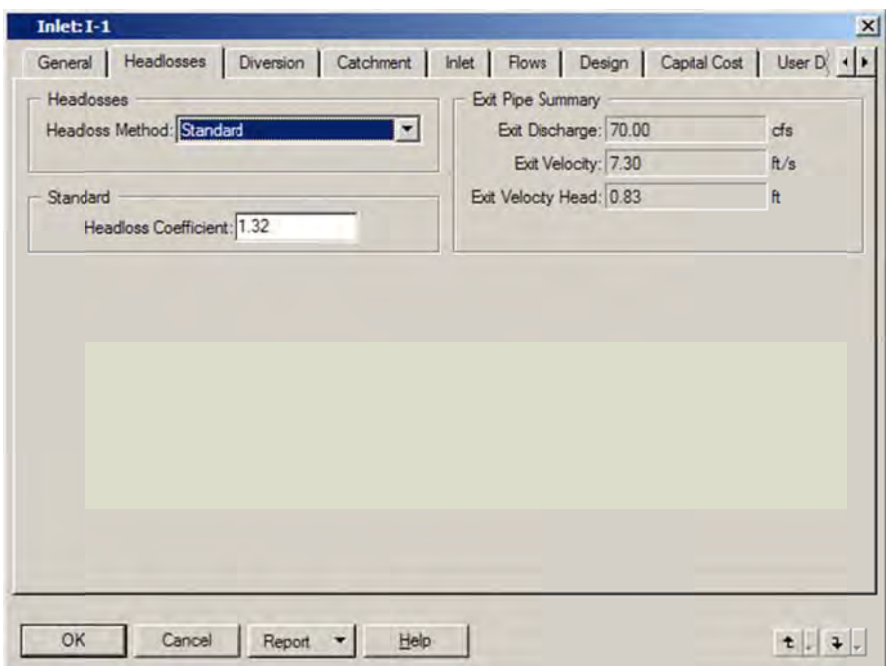
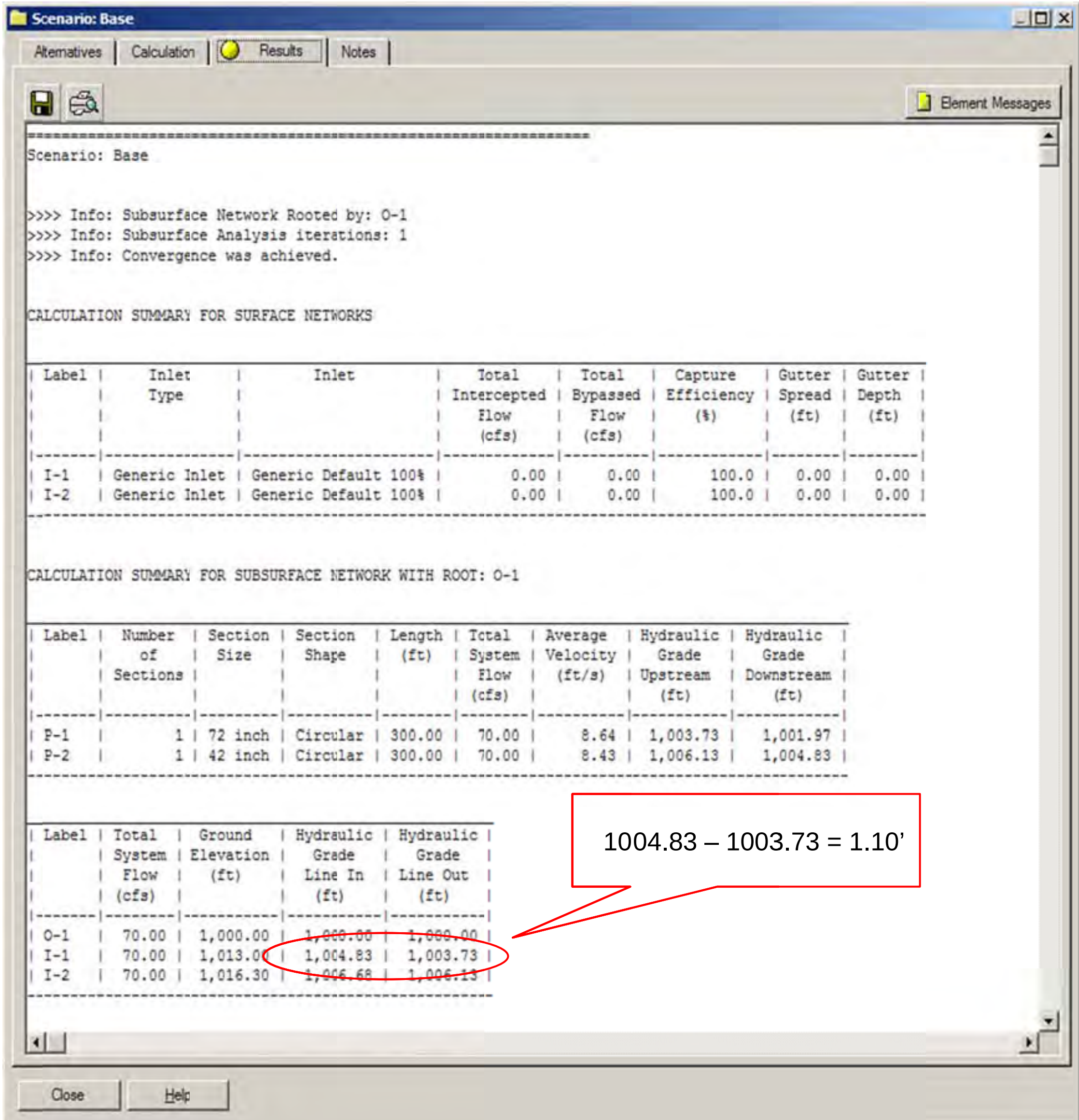



**Figure 14 -** Type in "1.32" for the headloss coefficient.
(This headloss coefficient was obtained from **Table 2** for the 90 degree angle.)

**Figures 15 and 16** show the HGL calculation results from both StormCAD and UD-Sewer. As the figures show, the total headloss between the upstream pipe 2 and the upstream pipe 1 as calculated using the standard method in StormCAD is 1.10 ft, which is close to the results of UD-Sewer.




Scenario: Base

>>>> Info: Subsurface Network Rooted by: O-1
>>>> Info: Subsurface Analysis iterations: 1
>>>> Info: Convergence was achieved.

CALCULATION SUMMARY FOR SURFACE NETWORKS

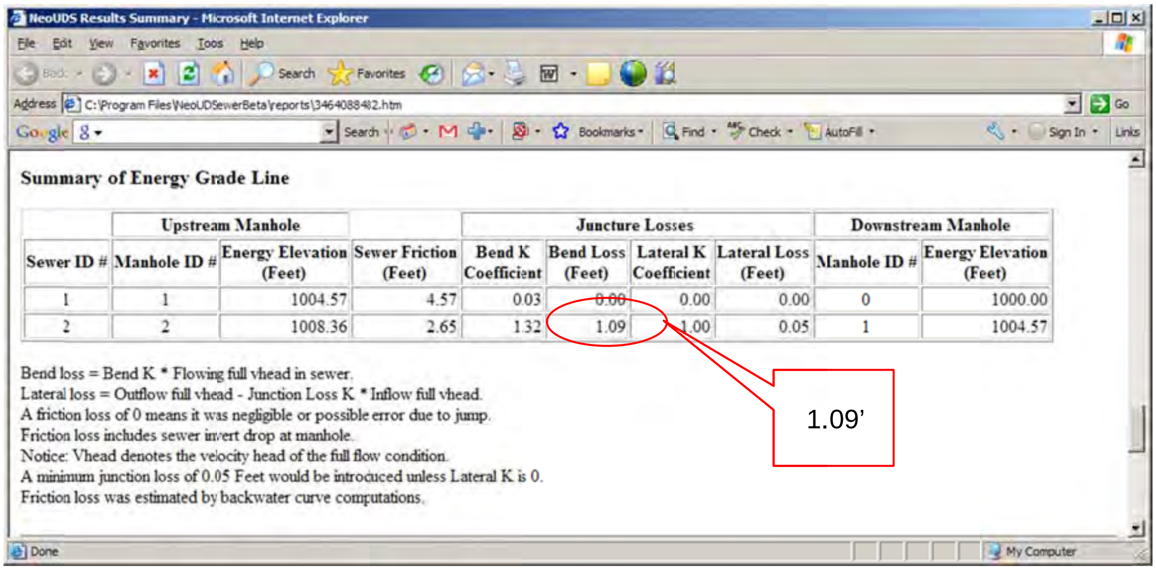
| Label | Inlet Type | Inlet | Total Intercepted Flow (cfs) | Total Bypassed Flow (cfs) | Capture Efficiency (%) | Gutter Spread (ft) | Gutter Depth (ft) |
|---|---|---|---|---|---|---|---|
| I-1 | Generic Inlet | Generic Default 100% | 0.00 | 0.00 | 100.0 | 0.00 | 0.00 |
| I-2 | Generic Inlet | Generic Default 100% | 0.00 | 0.00 | 100.0 | 0.00 | 0.00 |

CALCULATION SUMMARY FOR SUBSURFACE NETWORK WITH ROOT: O-1

| Label | Number of Sections | Section Size | Section Shape | Length (ft) | Total System Flow (cfs) | Average Velocity (ft/s) | Hydraulic Grade Upstream (ft) | Hydraulic Grade Downstream (ft) |
|---|---|---|---|---|---|---|---|---|
| P-1 | 1 | 72 inch | Circular | 300.00 | 70.00 | 8.64 | 1,003.73 | 1,001.97 |
| P-2 | 1 | 42 inch | Circular | 300.00 | 70.00 | 8.43 | 1,006.13 | 1,004.83 |

| Label | Total System Flow (cfs) | Ground Elevation (ft) | Hydraulic Grade Line In (ft) | Hydraulic Grade Line Out (ft) |
|---|---|---|---|---|
| O-1 | 70.00 | 1,000.00 | 1,000.00 | 1,000.00 |
| I-1 | 70.00 | 1,013.00 | 1,004.83 | 1,003.73 |
| I-2 | 70.00 | 1,016.30 | 1,006.68 | 1,006.13 |

**Figure 15 -** StormCAD HGL calculation output



**Summary of Energy Grade Line**

| | Upstream Manhole | | | Juncture Losses | | | | Downstream Manhole | |
|---|---|---|---|---|---|---|---|---|---|
| Sewer ID # | Manhole ID # | Energy Elevation (Feet) | Sewer Friction (Feet) | Bend K Coefficient | Bend Loss (Feet) | Lateral K Coefficient | Lateral Loss (Feet) | Manhole ID # | Energy Elevation (Feet) |
| 1 | 1 | 1004.57 | 4.57 | 0.03 | 0.00 | 0.00 | 0.00 | 0 | 1000.00 |
| 2 | 2 | 1008.36 | 2.65 | 1.32 | 1.09 | 1.00 | 0.05 | 1 | 1004.57 |

Bend loss = Bend K * Flowing full vhead in sewer.
Lateral loss = Outflow full vhead - Junction Loss K * Inflow full vhead.
A friction loss of 0 means it was negligible or possible error due to jump.
Friction loss includes sewer invert drop at manhole.
Notice: Vhead denotes the velocity head of the full flow condition.
A minimum junction loss of 0.05 Feet would be introduced unless Lateral K is 0.
Friction loss was estimated by backwater curve computations.



**Figure 16 -** UD-Sewer output file

# 7. Conclusion

AMEC believes that the inconsistencies between StormCAD HGL calculation results and UD-Sewer calculation results are a critical issue for water resource engineers in the Denver area. For example, the City of Aurora prohibits the use of StormCAD for HGL calculations, which causes problems when trying to design a new development if the existing system was designed with StormCAD. Developing a method that would allow engineers to use StormCAD and still get results that are consistent with UD-Sewer and acceptable to UDFCD, the City of Aurora, and others will provide significant benefits.

The results of this study show that StormCAD's Standard Method headloss methodology can replicate HGL results from the UD-Sewer model. In addition, the analytical approach demonstrated that a K value (when used within the engineering guidelines) can be developed to replicate UD-Sewer HGL results.

The inconsistencies resulting from the use of multiple hydraulic software packages have been identified through the results of the bend and lateral loss comparisons between UD-Sewer and StormCAD. The StormCAD conversion table provides a guide to engineers that allows for an accurate HGL and headloss results consistent with those of UD-Sewer.

The intent of this study was to allow engineers to use StormCAD to calculate HGL with the same confidence that comes with UD-Sewer. Several assumptions and limitations exist within this study and therefore the engineer must adhere to the guidelines that have been established for the conversion table when using StormCAD to replicate UD-Sewer results.

# 8. References

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# Appendix A: UD-Sewer's User Manual (Summary)

## Bend Loss

Bend loss is often estimated as a fraction of the full flow velocity head in the incoming sewer. UD-Sewer bend loss equation is as follows:

$$E_1 = E_4 + H_b$$

$$H_b = K_b \frac{V_f^2}{2g}$$

where, $H_b$ = Bend loss

$V_f$ = full flow velocity in the sewer coming to the manhole

$K_b$ = Bend loss coefficient

## Lateral Loss

Lateral losses are only applicable to the trunk line sewers. Lateral losses count for the additional turbulence caused by the branch sewers. The value of lateral loss coefficient, $K_m$, is determined by the angle between the branch line and the main line. UD-Sewer lateral loss equation is as follows:

$$E_1 = E_4 + H_b + H_m$$

$$H_m = \frac{V_{fo}^2}{2g} - K_m \frac{V_{fi}^2}{2g}$$

where, Hb = Bend loss

Hm = Lateral loss

Vfo = full flow velocity of the outgoing sewer at manhole

Vfi = full flow velocity of incoming lateral at manhole

Km = Lateral loss coefficient

$$H_j = k_{bT} \cdot \left( \frac{V_{fT}^2}{2g} \right) + \left[ \left( \frac{V_{fo}^2}{2g} \right) - k_m \cdot \left( \frac{V_{fi}^2}{2g} \right) \right] + k_{bL} \cdot \left( \frac{V_{fi}^2}{2g} \right)$$

## Junction Loss

where, $Hj$ = UD-Sewer junction loss

$k_{bT}$ = Bend loss coefficient at truckling

$k_{bL}$ = Bend loss coefficient at lateral

$V_{fT}$ = full flow velocity of trunk line at manhole

$V_{fi}$ = full flow velocity of incoming lateral at manhole

$k_m$ = Lateral loss coefficient

$V_{fo}$ = full flow velocity of the outgoing sewer at manhole

# Appendix B: StormCAD User Manual (Summary)

## Headloss – Hec-22 Energy Method

Similar to the standard method, the HEC-22 Energy method (from the FHWA's *Urban Drainage Design Manual, Hydraulic Engineering Circular No. 22*) correlates structure headloss to the velocity head in the outlet pipe using a coefficient. Experimental studies have determined that this coefficient can be approximated by:

$$K = K_0 C_D C_d C_Q C_p C_B$$

Where: K = Adjusted headloss coefficient

KO = Initial headloss coefficient based on relative junction size

CD = Correction factor for the pipe diameter

Cd = Correction factor for flow depth

CQ = Correction for relative flow

Cp = Correction for plunging flow

CB = Correction factor for benching

## Headloss – Standard Method

The standard method calculates structure headloss based on the exit pipe's velocity. The exit velocity head is multiplied by a user-entered coefficient to determine the loss:

$$h_s = K \frac{V_0^2}{2g}$$

Where: $h_s$ = Structure headloss (ft, m)

$V_0$= Exit pipe velocity (ft/s, m/s)

*G* = Gravitational acceleration constant (ft/s$^2$, m/s$^2$)

*K* = Headloss coefficient (unitless)

## Headloss – Generic Method

The generic method computes the structure headloss by multiplying the velocity head of the exit pipe by the user-entered downstream coefficient and then subtracting the velocity head of the governing upstream pipe multiplied by the user-entered upstream coefficient.

$$h_s = K_o \cdot \frac{V_o^2}{2g} - K_1 \cdot \frac{V_1^2}{2g}$$

Where: hS = Structure headloss (ft, m)

VO = Exit pipe velocity (ft/s, m/s)

KO = Downstream coefficient (unitless)

V1 = Governing upstream pipe velocity (ft/s, m/s)

K1 = Upstream coefficient (unitless)

g = Gravitational acceleration constant (ft/s², m/s²)

## Headloss – AASHTO Method

The AASHTO method (as defined in the AASHTO *Model Drainage Manual*) for structure headloss is based on power-loss methodologies. This method can be summarized by the following equation:

$$h_s = (h_c + h_b + h_e) \cdot C_n \cdot C_s$$

Where: hS = Structure headloss (m, ft)

hC = Contraction loss (m, ft)

hb = Bend loss (m, ft)

he = Expansion loss (m, ft)

Cn = Correction factor for non-piped flow (unitless)

CS = Correction factor for shaping (unitless)

# Appendix C: Output Files for Test Cases

| Pipe Loss | | | | | | | |
|---|---|---|---|---|---|---|---|
| Flow Condition | | | Supercritical | | | | |
| Total Flow | | | 70 | | | | |
| Case # | | | 161 | 163 | 60 | 61 | 62 |
| Outlet elevation | | (ft) | 1000 | 1000 | 1000 | 1000 | 1000 |
| Pipe1 | Length | (ft) | 10 | 20 | 100 | 200 | 300 |
| | Slop | % | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| | Manning N | n | 0.013 | 0.013 | 0.013 | 0.013 | 0.013 |
| UD Sewer | Upstream | (ft) | 1002.77 | 1002.83 | 1003.29 | 1003.81 | 1004.31 |
| | Downstream | (ft) | 1002.81 | 1002.81 | 1002.81 | 1002.81 | 1002.81 |
| | Pipe Loss | (ft) | -0.04 | 0.02 | 0.48 | 1 | 1.5 |
| StormCAD | Upstream | (ft) | 1002.76 | 1002.83 | 1003.3 | 1003.82 | 1004.32 |
| | Downstream | (ft) | 1002.62 | 1002.62 | 1002.62 | 1002.62 | 1002.62 |
| | Pipe Loss | (ft) | 0.14 | 0.21 | 0.68 | 1.2 | 1.7 |
| Hec-22 | Upstream | (ft) | | | 1003.3 | 1003.82 | 1004.32 |
| | Downstream | (ft) | | | 1002.62 | 1002.62 | 1002.62 |
| | Pipe Loss | (ft) | | | 0.68 | 1.2 | 1.7 |
| AASHTO | Upstream | (ft) | | | 1003.3 | 1003.82 | 1004.32 |
| | Downstream | (ft) | | | 1002.62 | 1002.62 | 1002.62 |
| | Pipe Loss | (ft) | | | 0.68 | 1.2 | 1.7 |
| Generic | Upstream | (ft) | | | 1003.3 | 1003.82 | 1004.32 |
| | Downstream | (ft) | | | 1002.62 | 1002.62 | 1002.62 |
| | Pipe Loss | (ft) | | | 0.68 | 1.2 | 1.7 |

| Pipe Loss | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Flow Condition | | | Supercritical | | | | | | |
| Total Flow | | | 70 | | | | | | |
| Case # | | | 264 | 265 | 266 | 267 | 268 | 269 | 270 |
| Outlet elevation | | (ft) | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| Pipe1 | Length | (ft) | 10 | 20 | 30 | 50 | 100 | 200 | 300 |
| | Slop | % | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | Manning N | n | 0.013 | 0.013 | 0.013 | 0.013 | 0.013 | 0.013 | 0.013 |
| UD Sewer | Upstream | (ft) | 1003.07 | 1003.07 | 1003.07 | 1003.12 | 1003.62 | 1004.62 | 1005.62 |
| | Downstream | (ft) | 1002.14 | 1002.14 | 1002.14 | 1002.14 | 1002.14 | 1002.14 | 1002.14 |
| | Pipe Loss | (ft) | 0.93 | 0.93 | 0.93 | 0.98 | 1.48 | 2.48 | 3.48 |
| StormCAD | Upstream | (ft) | 1002.72 | 1002.82 | 1002.92 | 1003.12 | 1003.62 | 1004.62 | 1005.62 |
| | Downstream | (ft) | 1002.43 | 1002.36 | 1002.32 | 1002.27 | 1002.21 | 1002.16 | 1002.15 |
| | Pipe Loss | (ft) | 0.29 | 0.46 | 0.6 | 0.85 | 1.41 | 2.46 | 3.47 |

| Bend Loss | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Flow Condition | | | Supercritical (72" / 42") | | | | Subcritical (72" / 42") | | | |
| Slope | | | 1 | 1 | 1 | 1 | 0.5 | 0.5 | 0.5 | 0.5 |
| Total Flow | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 |
| Bend Angle | | | 0 | 45 | 60 | 90 | 0 | 45 | 60 | 90 |
| Case # | | | 49 | 50 | 51 | 52 | 149 | 150 | 151 | 152 |
| Outlet elevation | | (ft) | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| Manhole | Out | (ft) | 1003 | 1003 | 1003 | 1003 | 1001.5 | 1001.5 | 1001.5 | 1001.5 |
| | Invert | (ft) | 1003.3 | 1003.3 | 1003.3 | 1003.3 | 1001.8 | 1001.8 | 1001.8 | 1001.8 |
| | Discharge | (cfs) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NeoUD Sewer | Water El. | (ft) | 1005.35 | 1005.35 | 1005.35 | 1005.35 | 1003.85 | 1003.85 | 1003.85 | 1003.85 |
| | Bend Loss | (ft) | 0.01 | 0.31 | 0.52 | 1.09 | 0.02 | 0.31 | 0.52 | 1.09 |
| Standard | Upstream | (ft) | 1005.65 | 1005.73 | 1005.81 | 1005.9 | 1004.15 | 1004.23 | 1004.31 | 1004.4 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Downstream | (ft) | 1005.23 | 1005.23 | 1005.23 | 1005.23 | 1003.73 | 1003.73 | 1003.73 | 1003.73 |
| | Manhole Loss | (ft) | 0.42 | 0.5 | 0.58 | 0.67 | 0.42 | 0.5 | 0.58 | 0.67 |
| Hec-22 | Upstream | (ft) | 1005.25 | 1005.45 | 1005.49 | 1005.53 | 1003.75 | 1003.95 | 1003.99 | 1004.03 |
| | Downstream | (ft) | 1005.23 | 1005.23 | 1005.23 | 1005.23 | 1003.73 | 1003.73 | 1003.73 | 1003.73 |
| | Manhole | (ft) | 0.02 | 0.22 | 0.26 | 0.3 | 0.02 | 0.22 | 0.26 | 0.3 |
| AASHTO | Upstream | (ft) | 1005.77 | 1006.05 | 1006.09 | 1006.15 | 1004.27 | 1004.55 | 1004.59 | 1004.65 |
| | Downstream | (ft) | 1005.23 | 1005.23 | 1005.23 | 1005.23 | 1003.73 | 1003.73 | 1003.73 | 1003.73 |
| | Manhole Loss | (ft) | 0.54 | 0.82 | 0.86 | 0.92 | 0.54 | 0.82 | 0.86 | 0.92 |
| Generic | Upstream | (ft) | 1005.23 | 1005.23 | 1005.23 | 1005.23 | 1003.73 | 1003.73 | 1003.73 | 1003.73 |
| | Downstream | (ft) | 1005.23 | 1005.23 | 1005.23 | 1005.23 | 1003.73 | 1003.73 | 1003.73 | 1003.73 |
| | Manhole Loss | (ft) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Bend Loss

| Flow Condition | | | Surcharged (42" / 42") | | | | Large Pipes (72" / 54") | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Slope | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Total Flow | | | 110 | 110 | 110 | 110 | 70 | 70 | 70 | 70 |
| Bend Angle | | | 0 | 45 | 60 | 90 | 0 | 45 | 60 | 90 |
| Case # | | | 153 | 154 | 155 | 156 | 49L | 50L | 51L | 52L |
| Outlet elevation | | (ft) | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| Manhole | Out | (ft) | 1003 | 1003 | 1003 | 1003 | 1003 | 1003 | 1003 | 1003 |
| | Invert | (ft) | 1003.3 | 1003.3 | 1003.3 | 1003.3 | 1003.3 | 1003.3 | 1003.3 | 1003.3 |
| | Discharge | (cfs) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NeoUD Sewer | Water El. | (ft) | 1006.85 | 1006.85 | 1006.85 | 1006.85 | 1005.35 | 1005.35 | 1005.35 | 1005.35 |
| | Bend Loss | (ft) | 0.06 | 0.77 | 1.28 | 2.68 | 0.01 | 0.11 | 0.19 | 0.4 |
| Standard | Upstream | (ft) | 1007.71 | 1007.92 | 1008.12 | 1008.32 | 1005.65 | 1005.73 | 1005.81 | 1005.9 |
| | Downstream | (ft) | 1006.7 | 1006.7 | 1006.7 | 1006.7 | 1005.23 | 1005.23 | 1005.23 | 1005.23 |
| | Manhole Loss | (ft) | 1.01 | 1.22 | 1.42 | 1.62 | 0.42 | 0.5 | 0.58 | 0.67 |
| Hec-22 | Upstream | (ft) | 1006.81 | 1007.78 | 1008 | 1008.18 | 1005.25 | 1005.45 | 1005.49 | 1005.53 |
| | Downstream | (ft) | 1006.7 | 1006.7 | 1006.7 | 1006.7 | 1005.23 | 1005.23 | 1005.23 | 1005.23 |
| | Manhole | (ft) | 0.11 | 1.08 | 1.3 | 1.48 | 0.02 | 0.22 | 0.26 | 0.3 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| AASHTO | Upstream | (ft) | 1007.92 | 1008.87 | 1009.05 | 1009.34 | 1005.77 | 1006.05 | 1006.09 | 1006.15 |
| | Downstream | (ft) | 1006.7 | 1006.7 | 1006.7 | 1006.7 | 1005.23 | 1005.23 | 1005.23 | 1005.23 |
| | Manhole Loss | (ft) | 1.22 | 2.17 | 2.35 | 2.64 | 0.54 | 0.82 | 0.86 | 0.92 |
| Generic | Upstream | (ft) | 1007.2 | 1007.31 | 1007.41 | 1007.51 | 1005.23 | 1005.23 | 1005.23 | 1005.23 |
| | Downstream | (ft) | 1006.7 | 1006.7 | 1006.7 | 1006.7 | 1005.23 | 1005.23 | 1005.23 | 1005.23 |
| | Manhole Loss | (ft) | 0.5 | 0.61 | 0.71 | 0.81 | 0 | 0 | 0 | 0 |

Lateral Loss

| Flow Condition | | | Supercritical | | | | Subcritical | | |
|---|---|---|---|---|---|---|---|---|---|
| Slope | | | 1 | 1 | 1 | 1 | 0.5 | 0.5 | 0.5 |
| Total Flow | | | 70+70 | 70+70 | 70+70 | 70+70 | 70+70 | 70+70 | 70+70 |
| Bend Angle | | | 0 | 45 | 60 | 90 | 0 | 45 | 60 |
| Case # | | | 49 | 53 | 54 | 55 | 149 | 250 | 251 |
| Outlet elevation | | (ft) | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| Manhole | Out | (ft) | 1003 | 1003 | 1003 | 1003 | 1001.5 | 1003 | 1003 |
| | Invert | (ft) | 1003.3 | 1003.3 | 1003.3 | 1003.3 | 1001.8 | 1003.3 | 1003.3 |
| | Discharge | (cfs) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NeoUD Sewer | Water El. | (ft) | 1005.35 | 1006.23 | 1006.23 | 1006.23 | 1003.85 | 1004.73 | 1004.73 |
| | Manhole Loss | (ft) | 0.02 | 0.38 | 0.62 | 1.29 | 0.02 | 0.38 | 0.62 |
| Standard | Upstream | (ft) | 1005.65 | 1007.24 | 1007.24 | 1007.37 | 1004.15 | 1005.74 | 1005.74 |
| | Downstream | (ft) | 1005.23 | 1006.21 | 1006.21 | 1006.21 | 1003.73 | 1004.71 | 1004.71 |
| | Manhole Loss | (ft) | 0.42 | 1.03 | 1.03 | 1.16 | 0.42 | 1.03 | 1.03 |
| Hec-22 | Upstream | (ft) | 1005.25 | 1006.25 | 1006.25 | 1006.25 | 1003.75 | 1004.74 | 1004.74 |
| | Downstream | (ft) | 1005.23 | 1006.21 | 1006.21 | 1006.21 | 1003.73 | 1004.71 | 1004.71 |
| | Manhole Loss | (ft) | 0.02 | 0.04 | 0.04 | 0.04 | 0.02 | 0.03 | 0.03 |
| AASHTO | Upstream | (ft) | 1005.77 | 1008.3 | 1008.42 | 1008.5 | 1004.27 | 1005.93 | 1005.98 |
| | Downstream | (ft) | 1005.23 | 1006.21 | 1006.21 | 1006.21 | 1003.73 | 1004.71 | 1004.71 |
| | Manhole Loss | (ft) | 0.54 | 2.09 | 2.21 | 2.29 | 0.54 | 1.22 | 1.27 |
| Generic | Upstream | (ft) | 1005.23 | 1007.04 | 1007.04 | 1007.15 | 1003.73 | 1004.71 | 1004.71 |
| | Downstream | (ft) | 1005.23 | 1006.21 | 1006.21 | 1006.21 | 1003.73 | 1004.71 | 1004.71 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Manhole Loss | (ft) | 0 | 0.83 | 0.83 | 0.94 | 0 | 0 | 0 |

| Lateral Loss | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Flow Condition | | | Surcharged | | | | Large Pipes | | | |
| Slope | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Total Flow | | | 110+110 | 110+110 | 110+110 | 110+110 | 70+70 | 70+70 | 70+70 | 70+70 |
| Bend Angle | | | 0 | 45 | 60 | 90 | 0 | 45 | 60 | 90 |
| Case # | | | 153 | 253 | 254 | 255 | 49L | 53L | 54L | 55L |
| Outlet elevation | | (ft) | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| Manhole | Out | (ft) | 1003 | 1003 | 1003 | 1003 | 1003 | 1003 | 1003 | 1003 |
| | Invert | (ft) | 1003.3 | 1003.3 | 1003.3 | 1003.3 | 1003.3 | 1003.3 | 1003.3 | 1003.3 |
| | Discharge | (cfs) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NeoUD Sewer | Water El. | (ft) | 1006.85 | 1007.05 | 1007.05 | 1007.05 | 1005.35 | 1006.23 | 1006.23 | 1006.23 |
| | Manhole Loss | (ft) | 0.2 | 0.88 | 1.55 | 3.17 | 0.01 | 0.35 | 0.47 | 0.72 |
| Standard | Upstream | (ft) | 1006.38 | 1008.51 | 1008.51 | 1008.69 | 1005.65 | 1007.24 | 1007.24 | 1007.37 |
| | Downstream | (ft) | 1005.83 | 1007.06 | 1007.06 | 1007.06 | 1005.23 | 1006.21 | 1006.21 | 1006.21 |
| | Manhole Loss | (ft) | 0.55 | 1.45 | 1.45 | 1.63 | 0.42 | 1.03 | 1.03 | 1.16 |
| Hec-22 | Upstream | (ft) | 1005.85 | 1007.13 | 1007.13 | 1007.13 | 1005.25 | 1006.25 | 1006.25 | 1006.25 |
| | Downstream | (ft) | 1005.83 | 1007.06 | 1007.06 | 1007.06 | 1005.23 | 1006.21 | 1006.21 | 1006.21 |
| | Manhole Loss | (ft) | 0.02 | 0.07 | 0.07 | 0.07 | 0.02 | 0.04 | 0.04 | 0.04 |
| AASHTO | Upstream | (ft) | 1006.81 | 1009.18 | 1009.36 | 1009.65 | 1005.77 | 1008.3 | 1008.42 | 1008.5 |
| | Downstream | (ft) | 1005.83 | 1007.06 | 1007.06 | 1007.06 | 1005.23 | 1006.21 | 1006.21 | 1006.21 |
| | Manhole Loss | (ft) | 0.98 | 2.12 | 2.3 | 2.59 | 0.54 | 2.09 | 2.21 | 2.29 |
| Generic | Upstream | (ft) | 1005.83 | 1007.7 | 1007.7 | 1007.78 | 1005.23 | 1007.04 | 1007.04 | 1007.15 |
| | Downstream | (ft) | 1005.83 | 1007.06 | 1007.06 | 1007.06 | 1005.23 | 1006.21 | 1006.21 | 1006.21 |
| | Manhole Loss | (ft) | 0 | 0.64 | 0.64 | 0.72 | 0 | 0.83 | 0.83 | 0.94 |