Scattergraph Principles and Practice

Evaluating Self-Cleansing in Existing Sewers Using the Tractive Force Method

Kevin L. Enfinger, P.E. and Paul S. Mitchell, P.E.

ADS Environmental Services
340 The Bridge Street, Suite 204 │Huntsville, Alabama 35806 │www.adsenv.com/scattergraph

ABSTRACT The Tractive Force Method is used to design sewers with self-cleansing conditions based on a critical shear stress. The authors have extended the use of the tractive force approach from the design of new sewers to the evaluation of existing sewers under actual conditions. Self-cleansing conditions are assessed by evaluating flow monitor data on a scattergraph using a critical shear stress curve. Existing sewers with adequate self-cleansing conditions are readily identified, as well as those with a potential for silt, sediment, or debris accumulation.

Practical examples from flow monitor locations throughout the United States are provided, demonstrating the application of the Tractive Force Method to existing sewers. The authors applied this method to over 200 existing sewers where flow monitor data were available and compared the results with independent silt observations. Based on these results, the general effectiveness of the tractive force approach for the self-cleansing design of sanitary sewers is validated, and the findings support its use for the self-cleansing design of new sewers.

KEY WORDS Flow Monitoring, Scattergraph, Self-Cleansing Velocity, Tractive Force

Introduction

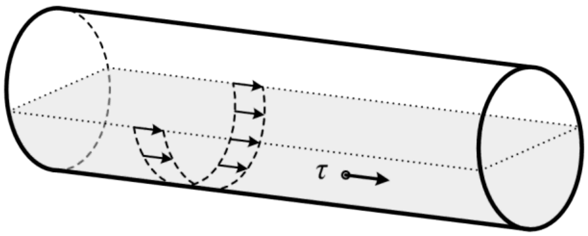
Self-cleansing is an important aspect of sanitary sewer design and is desired to minimize the deposition of silt, sediment, and debris. The Tractive Force Method is used to design sewers to achieve self-cleansing conditions based on a required critical shear stress and is recommended by the American Society of Civil Engineers (ASCE) and the Water Environment Federation (WEF).[1]

The use of the Tractive Force Method can also be extended from the design of new sewers to the evaluation of existing sewers. The scattergraph is a graphical tool that provides insight into the performance of existing sewers through a simple and intuitive display of flow monitor data. The resulting patterns form characteristic signatures that reveal important information about conditions within a sewer.[2] Through the application of a critical shear stress curve, the scattergraph can also be used to evaluate self-cleansing flow conditions in existing sewers under actual conditions. This application is developed and discussed in this paper.

Shear Stress

Self-cleansing conditions within a sewer are directly related to shear stress. As wastewater flows within a sewer, it exerts an average boundary shear stress, or *tractive force*, on the sewer, as depicted in Figure 1 and described in Equation (1).

FIGURE 1: Shear Stress Exerted by Wastewater Flow



$$\tau = \gamma \mathrm{RS} \tag{1}$$

where: τ = average shear stress, $\mathrm{lb/ft^2}$
γ = specific weight of water, $\mathrm{lb/ft^3}$
R = hydraulic radius, ft
S = slope of the energy gradient, ft/ft

Flow conditions are classified as self-cleansing when the actual shear stress (τ) is greater than or equal to a specified critical shear stress (τ_c) at a defined frequency of occurrence.[1]

The critical shear stress needed to maintain self-cleansing conditions depends on the characteristics of the wastewater solids. Observations of these characteristics from wastewater in the United Kingdom are provided in Figure 2, as reported by Butler, May, and Ackers.[3]

FIGURE 2: Wastewater Solids Characteristics in the United Kingdom

Solids Type	Transport Mode	Median Size d_{50} mm			Specific Gravity		
		Low	········	High	Low	········	High
Sanitary	Suspension	0.01	0.04	0.06	1.01	1.40	1.60
Storm Water	Suspension	0.02	0.06	0.10	1.10	2.00	2.50
Grit	Bedload	0.30	0.75	1.00	2.30	2.60	2.70

Note that solids with a smaller size and a lower specific gravity are transported in suspension within the wastewater, while solids with a larger size and a higher specific gravity are more likely to be transported as bedload along the invert of the sewer. Consequently, if the average shear stress is sufficient to transport a *design particle* as bedload, then all smaller particles will also be effectively transported, either in suspension or as bedload. Therefore, the design particle recommended as the basis for self-cleansing sewer design using the Tractive Force Method is a 1.0-mm grit particle with a specific gravity of 2.70.[1]

Raths and McCauley have previously investigated the critical shear stress needed to transport grit particles of various sizes as bedload within a sewer.[4] Their results are summarized in Equation (2) and indicate that a critical shear stress of 0.0181 lb/ft^2 is required to transport the recommended design particle.[5]

$$\tau_c = 0.0181(D_p)^{0.277} \tag{2}$$

where: τ_c = critical shear stress, lb/ft^2
D_p = nominal diameter of design particle, mm

The critical shear stress can be related to flow velocity using a simple algebraic rearrangement to express Equation (1) in terms of the slope of the energy gradient associated with a specified critical shear stress as shown in Equation (3).

$$S = \frac{\tau_c}{\gamma R} \tag{3}$$

where: S = slope of the energy gradient, ft/ft
τ_c = critical shear stress, lb/ft^2
γ = specific weight of water, lb/ft^3
R = hydraulic radius, ft

The critical shear stress is then incorporated into the Manning Equation by substituting Equation (3) into Equation (4) as shown in Equation (5) and simplified in Equation (6) to express a self-cleansing flow velocity associated with a specified critical shear stress as a function of flow depth (d).[6]

$$v = \frac{1.486}{n} R^{2/3} S^{1/2} \tag{4}$$

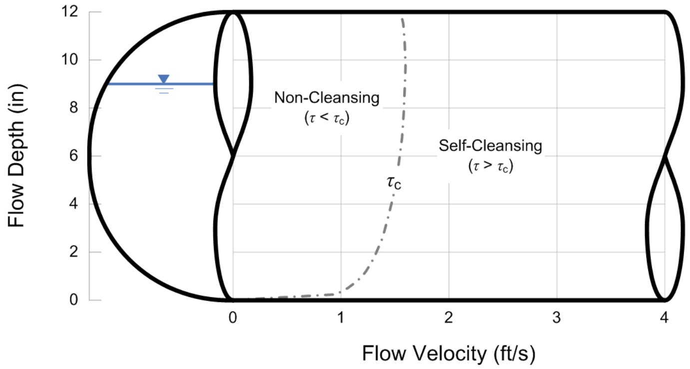
$$v_{sc} = \frac{1.486}{n} R^{2/3} \left(\frac{\tau_c}{\gamma R}\right)^{1/2} \tag{5}$$

$$v_{sc} = \frac{1.486}{n} R^{1/6} \left(\frac{\tau_c}{\gamma}\right)^{1/2} \tag{6}$$

where: v = flow velocity, ft/s
v_{sc} = self-cleansing flow velocity, ft/s
n = roughness coefficient
R = hydraulic radius, ft
S = slope of the energy gradient, ft/ft
τ_c = critical shear stress, lb/ft^2
γ = specific weight of water, lb/ft^3

Self-cleansing conditions defined by the Tractive Force Method can be illustrated using a critical shear stress curve by solving Equation (6) for $0 < d \leq D$ and plotting the results on a scattergraph.[7] The result is shown in Figure 3.

FIGURE 3: Scattergraph with Critical Shear Stress Curve



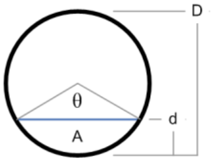
Self-cleansing is achieved when flow conditions occur to the right of the critical shear stress curve at a defined frequency of occurrence. Otherwise, self-cleansing is not achieved, and silt, sediment, and debris accumulation are likely to occur. An example is provided on the following page to demonstrate the construction of a critical shear stress curve on a scattergraph.

EXAMPLE Construct a critical shear stress curve on a scattergraph for a 24-in sewer where $\tau_c = 0.0181$ lb/ft^2.

Solution

Use Equation (6) to calculate v_{sc} for $0 < d \leq D$. For this example, assume $n = 0.013$ and $\gamma = 62.3$ lb/ft^3.

For a circular sewer,[8]



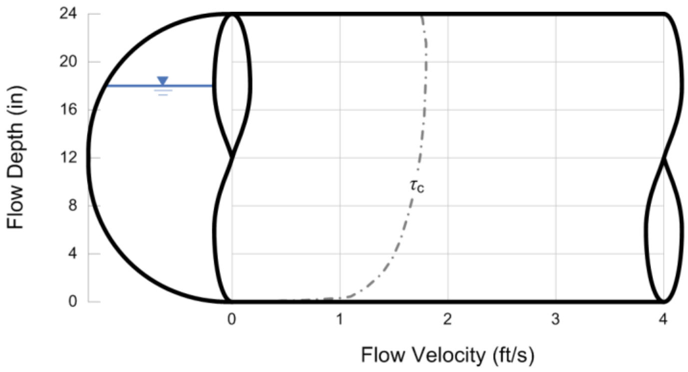
$$\theta = 2\cos^{-1}(1 - 2d/D)$$

$$A = (D^2/8)(\theta - \sin\theta)$$

$$P = D\theta/2$$

d	θ	A	P	R	v_{sc}
in	°	ft^2	ft	ft	ft/s
0	0	0.00	0.00	0.00	0.00
4	96	0.34	1.68	0.20	1.50
8	141	0.92	2.46	0.37	1.65
12	180	1.57	3.14	0.50	1.74
16	219	2.22	3.82	0.58	1.78
20	264	2.80	4.60	0.61	1.79
24	360	3.14	6.28	0.50	1.74

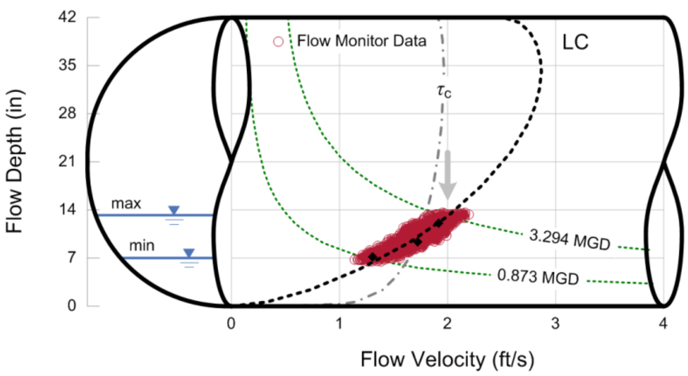
These results provide the necessary information to construct a critical shear stress curve on a scattergraph, as shown below:



Self-Cleansing in Existing Sewers

The scattergraph provides an effective means to assess self-cleansing conditions in existing sewers with *human viewing speed* by evaluating flow monitor data with respect to a critical shear stress curve. A graphical application of the Tractive Force Method is shown in Figure 4, depicting a scattergraph of an existing sewer that operates under self-cleansing conditions.

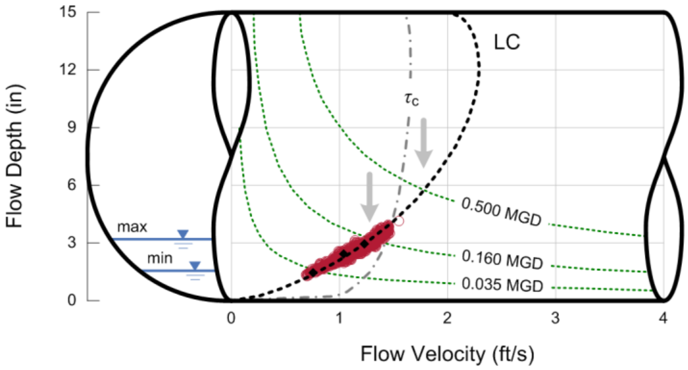
FIGURE 4: Scattergraph of Self-Cleansing Sewer



Flow monitor data (○) are plotted on the scattergraph and reveal the actual operating conditions within the sewer. Manual confirmations (◆) are also shown and provide a means to evaluate the accuracy of the flow monitor.[2] The Manning Equation is used to generate a *pipe curve* (---) that effectively describes the observed flow monitor data, and the minimum and maximum hourly average dry weather flow rates ($Q_{min\text{-}D}$ and $Q_{max\text{-}D}$) are depicted using iso-Q lines (---).[9,10] A critical shear stress curve is then plotted. If $Q_{max\text{-}D}$ occurs to the right of the critical shear stress curve, as depicted by the arrow in Figure 4, then the actual shear stress exceeds the required critical shear stress at least once per day, and self-cleansing conditions are satisfied based on the Tractive Force Method. If $Q_{max\text{-}D}$ occurs to the left of the critical shear stress curve, then the actual shear stress does not exceed the required critical shear stress at the defined frequency of occurrence, and silt, sediment, and debris accumulation may occur.

Non-cleansing conditions in existing sewers may be classified as either Type I or Type II. Type I non-cleansing conditions include sewers that operate under uniform flow conditions, but do not have sufficient flow to generate a shear stress in excess of the required critical shear stress. A scattergraph of an existing sewer that operates under Type I non-cleansing conditions is shown in Figure 5.

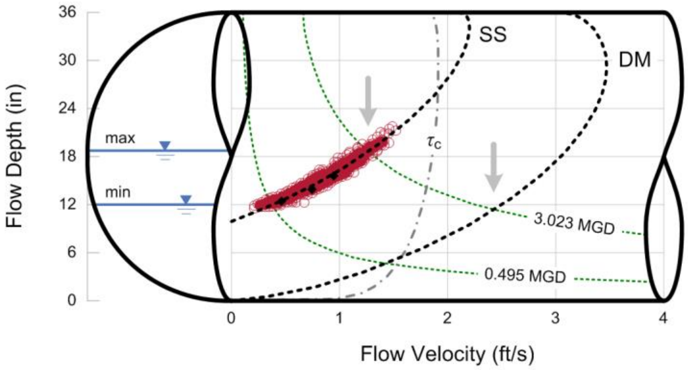
FIGURE 5: Scattergraph of Non-Cleansing Sewer – Type I



These conditions often occur early in the service life of a sewer when actual sewer flows are far less than those for which the sewer was designed. This sewer is capable of operating under self-cleansing conditions, but only if $Q_{max\text{-}D}$ is increased until the required critical shear stress is exceeded.

Type II non-cleansing conditions include sewers that operate under non-uniform flow conditions caused by backwater effects resulting from a variety of downstream obstructions, or *dead dogs*. Examples include offset joints, debris, and other related conditions.[9] A scattergraph of an existing sewer that operates under Type II non-cleansing conditions is shown in Figure 6.

FIGURE 6: Scattergraph of Non-Cleansing Sewer – Type II

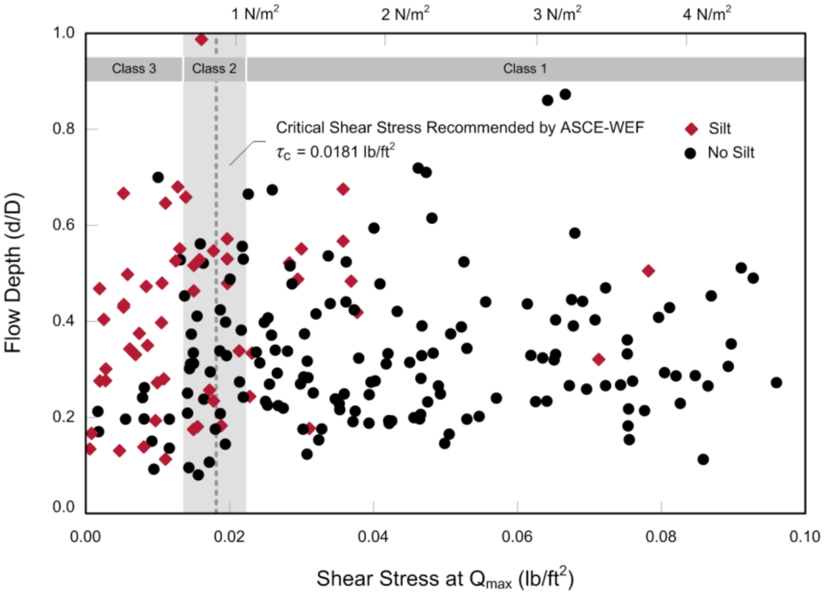


For a given $Q_{max\text{-}D}$, observed flow conditions are deeper and slower than expected, resulting in an actual shear stress that is less than the required critical shear stress. This sewer is capable of operating under self-cleansing conditions, but only if the *dead dog* is removed, and uniform flow conditions are restored.

Evaluation

To evaluate the effectiveness of the Tractive Force Method at predicting sewers that are likely to have silt, sediment, or debris problems, the authors applied the tractive force methodology as outlined in this paper to flow monitor data from over 200 existing sewers located throughout the United States. Tractive force predictions were then compared with independent silt observations, and the results are summarized in Figure 7.

FIGURE 7: Self-Cleansing Predictions vs. Observations in Existing Sewers



This exercise was not designed as a controlled experiment, but rather a practical test of the Tractive Force Method based on conditions commonly found in the urban sewer environment. The results were obtained from sewers ranging from 8 inches to 108 inches in diameter and were based on flow monitor data obtained from a 30-day monitoring period. Sewers predicted to be self-cleansing are shown to the right of the recommended critical shear stress, and sewers predicted to be non-cleansing are shown to the left. Independent silt observations were gathered over a subsequent 12-month observation period. Sewers where silt was observed are denoted in red (◆), and sewers where silt was not observed are denoted in black (●).

Based on these results, the general effectiveness of the tractive force approach for the self-cleansing design of sanitary sewers is illustrated. Some discrepancies between tractive force predictions and silt observations were noted, but most occurred within a +/-20% tolerance of the recommended critical shear stress. Based on these results, a classification system is proposed to indicate the self-cleansing status of existing sewers relative to the Tractive Force Method. Class 1 is defined as *self-cleansing* ($\tau > \tau_c$+20%). Class 2 is defined as *marginal cleansing* (τ_c-20% $\leq \tau \leq \tau_c$+20%), and Class 3 is defined as *non-cleansing* ($\tau < \tau_c$-20%).

Silt observations were identified at 12 flow monitor locations, despite having a shear stress at $Q_{max\text{-}D}$ greater than 120% of the recommended critical shear stress. These locations were further evaluated, and explanations were identified for eight of these locations, including a cohesive sediment layer at one location, gravel and construction debris at another location, several abandoned flume structures that were catching and accumulating debris, and nearby bar screens that were not effectively cleaned.

Conclusion

The Tractive Force Method is used to design sewers with self-cleansing conditions based on a critical shear stress and can be extended from the design of new sewers to the evaluation of existing sewers under actual conditions. Self-cleansing conditions can be determined by evaluating flow monitor data on a scattergraph using a critical shear stress curve. Existing sewers with adequate self-cleansing conditions are readily identified, as well as those with a potential for silt, sediment, or debris accumulation. Practical application of this method to over 200 existing sewers demonstrates the general effectiveness of the tractive force approach and supports its use for the self-cleansing design of new sewers.

Symbols and Notation

The following symbols and notation are used in this paper:

VARIABLES

d = flow depth, in or ft
v = flow velocity, ft/s
Q = flow rate, ft^3/s or MGD
n = roughness coefficient
R = hydraulic radius, ft
S = slope of the energy gradient, ft/ft
τ = average shear stress, lb/ft^2
D = diameter, in or ft
A = wetted area, ft^2
P = wetted perimeter, ft
γ = specific weight of water, lb/ft^3

SUBSCRIPTS

$_{c}$ = critical
$_{sc}$ = self cleansing
$_{DM}$ = Design Method
$_{LC}$ = Lanfear-Coll Method
$_{SS}$ = Stevens-Schutzbach Method
$_{min\text{-}D}$ = dry weather mininum
$_{max\text{-}D}$ = dry weather maximum

Acknowledgement

The authors acknowledge David Butler and LaVere Merritt for helpful discussions regarding the self-cleansing design of sanitary sewers. Special thanks are also extended to Patrick Stevens for his technical review.

References

1. American Society of Civil Engineers (2007). *Gravity Sanitary Sewer Design and Construction*, 2nd Edition, ASCE Manuals and Reports on Engineering Practice No. 60, American Society of Civil Engineers: Reston, VA.

2. Enfinger, K.L. and Keefe, P.N. (2004). "Scattergraph Principles and Practice – Building a Better View of Flow Monitor Data," KY-TN Water Environment Association Water Professionals Conference; Nashville, TN.

3. Butler, D., May, R.W.P., and Ackers, J.C. (1996). "Sediment Transport in Sewers – Part 1: Background," Proceedings of the Institution of Civil Engineers, *Water, Maritime, and Energy*, Volume 118, Page 103-112.

4. Raths, C.W. and McCauley, R.R. (1962). "Deposition in a Sanitary Sewer," *Water and Sewage Works*, Volume 109, Issue 5, p. 192-197.

5. Walski, T.M., Barnard, T.E., Harold, E., Merritt, L.B., Walker, N., & Whitman, B.E. (2004). *Wastewater Collection System Modeling and Design*, Haestad Press, Waterbury, CT.

6. Yao, K.M. (1974). "Sewer Line Design Based on Critical Shear Stress," *Journal of the Environmental Engineering Division, Proceedings of the American Society of Civil Engineers*, Volume 100, Number EE2, p. 507- 520.

7. Moraitis, P. (1999). "Development of Gravity Flow Pipe Design Charts." Unpublished Undergraduate Project for Professor David Butler. Imperial College, Department of Civil and Environmental Engineering, London.

8. Butler, D. and Davies, J.W. (2000). *Urban Drainage*. E & FN Spon, London.

9. Enfinger, K.L. and Kimbrough, H.R. (2004). "Scattergraph Principles and Practice – A Comparison of Various Applications of the Manning Equation," *Proceedings of the Pipeline Division Specialty Conference*; San Diego, CA; American Society of Civil Engineers: Reston, VA.

10. Enfinger, K.L. and Stevens, P.L. (2006). "Scattergraph Principles and Practice – Tools and Techniques to Evaluate Sewer Capacity," *Proceedings of the Pipeline Division Specialty Conference*; Chicago, IL; American Society of Civil Engineers: Reston, VA.

This technical paper was first presented on May 19, 2010 at the American Society of Civil Engineers World Environmental & Water Resources Congress held in Providence, RI and can be referenced as shown below. This version was last updated on March 28, 2016.

Enfinger, K.L. and Mitchell, P.S. (2010). "Scattergraph Principles and Practice – Evaluating Self-Cleansing in Existing Sewers Using the Tractive Force Method," *Proceedings of the World Environmental & Water Resources Congress 2010*; Providence, RI; American Society of Civil Engineers: Reston, VA.