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Deposition and Scour in Stormwater Pipes in WinSLAMM

Contents

Introduction

This memo describes the theory and example calculations of sediment deposition and subsequent scour of stormwater particulates in stormwater pipes. These methods do not apply to grass swales (deposition processes are included in those model sections).

Deposition occurs when particles settle through the flowing water to the bottom of the pipe. Hydraulic characteristics affecting deposition include the water depth and water velocity. Stokes and Newtons settling equations are used to calculate which particle sizes (depending on their densities) will settle during the length of flow through the pipe. Scour conditions are related to shear stress which is calculated using the hydraulic radius of flow and the hydraulic gradient of the flow. The deposition and scour conditions relate to the size of the particulates (and their density and cohesiveness). These calculations therefore identify which particle sizes are stable, which move as bed load, and which are fully suspended and move with the water. These conditions vary for different flow conditions during storms and therefore are calculated for short time steps.

Pipe Flow Hydraulics

Pipe hydraulic information is used to calculate the depth of flow in the pipe, the water velocity, and the shear stress. The depth of flow and velocity (along with length) are used to calculate the settling potential of stormwater particulates in the flow water, while the depth of flow (and corresponding hydraulic radius) along with the hydraulic gradient are used to calculate the shear stress between the flowing water and any sediment on the bottom of the pipe. High shear stresses can scour some of the previously deposited sediment.

Manning's equation is a common method to calculate the full flowing pipe discharge (Q_{full}) capacity for a given pipe diameter (D), slope (S), and roughness (n):

$$Q_{full} = \frac{0.46}{n} D^{8/3}\sqrt{S}$$

Where: Q_{full} = discharge of pipe flowing full (ft^3/sec)
D = pipe diameter (ft)
n = Manning's roughness (0.013 typical value for smooth concrete pipes in good condition)
S = hydraulic gradient (ft/ft); assumed to be the pipe slope under normal flow conditions (required for use of the Manning equation)

Figure 1 show plots of the Manning's equation full flowing pipe Q_{full} discharge and V_{full} velocity values as a function of pipe slope, for a 3 ft diameter pipe with a roughness value of 0.013. The full flowing velocity (V_{full}) is the discharge value divided by the cross-sectional area of the pipe. For a 3 ft diameter pipe, the cross-sectional area is 7.1 ft^2.

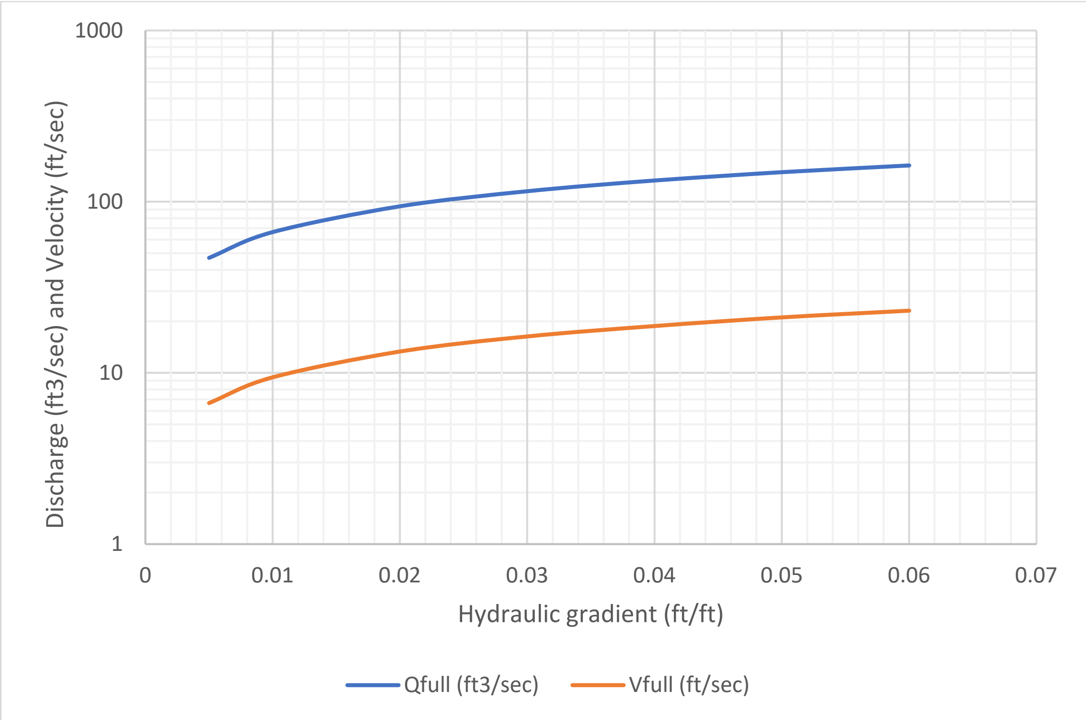


Figure 1. Example Manning's equation calculation for Q_{full} and V_{full} for 3 ft diameter pipe (n = 0.013) for different hydraulic gradients.

The actual stormwater discharge (Q) is calculated by WinSLAMM. The ratio of the actual discharge to the full flowing pipe discharge (Q_{full}) is used to calculate the flow depth (d) to pipe diameter (D) ratio, and then the actual velocity (V) (from the V/V_{full} relationship), and the hydraulic radius (R), shown in the following figures. The velocity value is needed to calculate the settling potential of stormwater particulates flowing along the pipe, and the hydraulic radius is used to calculate the shear stress value used to calculate potential scour and resuspension of sediment in the pipe.

The depth of flow in a partially full pipe is calculated using Camp's curve, shown in Figure 2. This figure relates the full pipe capacity discharge (Q_{full}) to the actual discharge (Q), the full pipe water velocity (V_{full}) to the actual velocity (V), to the ratio of the actual flow depth (y) to the pipe diameter (D). Figures 3 and 4 are rough regression estimates showing the d/D relationships to Q/Q_{full} and Q/Q_{full} to V/V_{full}.

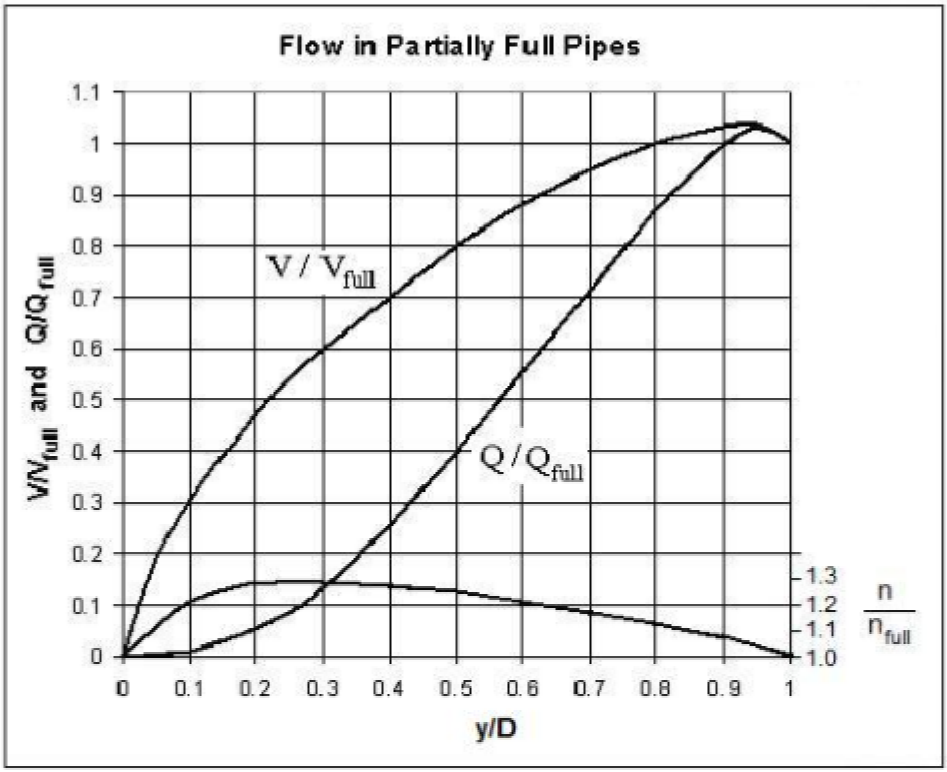


Figure 2. Camp's curve relating velocity/velocity$_{full}$ and discharge/discharge$_{full}$ to depth to diameter ratio (https://www.cedengineering.com/userfiles/Partially%20Full%20Pipe%20Flow%20Calculations.pdf).

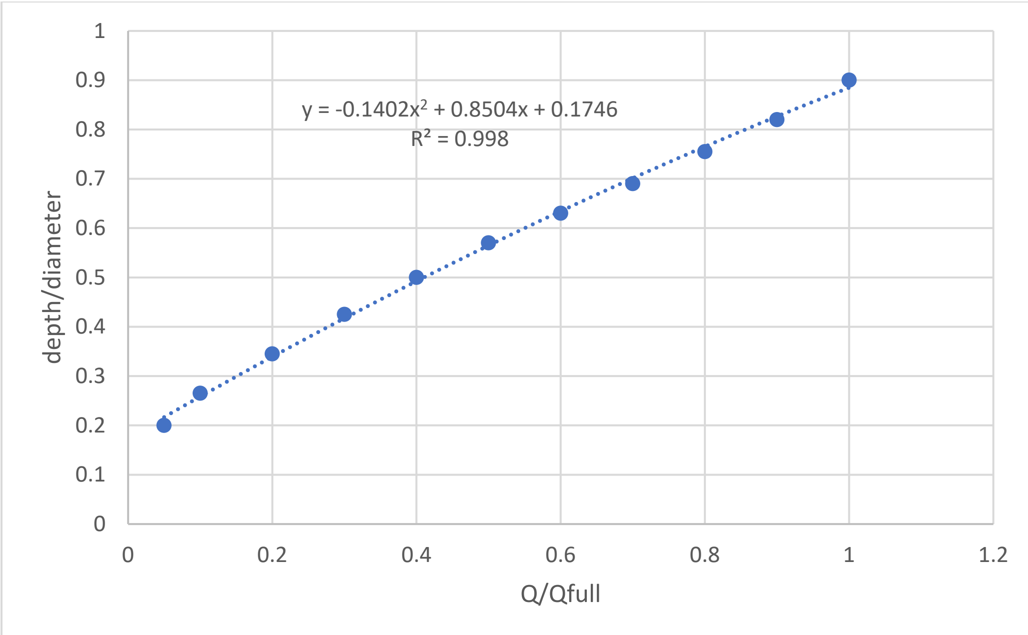


Figure 3. Depth/diameter and discharge/discharge$_{full}$ relationship (rough estimate by regression).

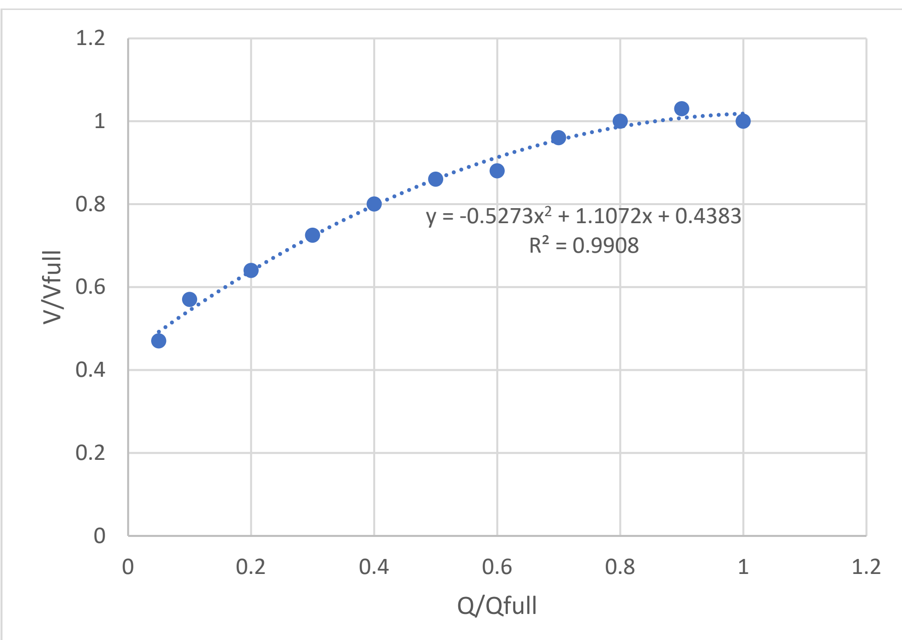


Figure 4. Velocity/velocity$_{full}$ and discharge/discharge$_{full}$ relationship (rough estimate by regression).

Figure 5 shows additional hydraulic relationships for partially flowing pipes. The hydraulic radius (R), the ratio of the cross-sectional area to wetted perimeter, is used when calculating the shear stress. Figure 6 is a rough regression approximation for calculating the hydraulic radius based on the depth (d) to pipe diameter (D) ratio.

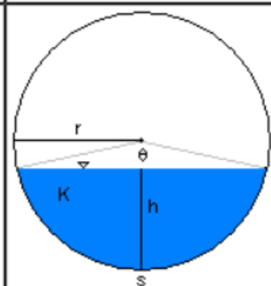
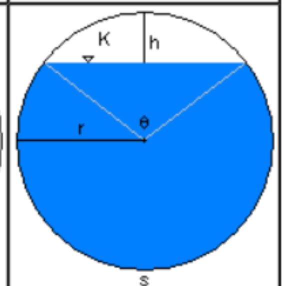
step	solve for	if flow depth < radius	if flow depth ≥ radius
			
1	circular segment height	$h = d$	$h = 2r - d$
2	central angle	$\theta = 2\arccos\left(\frac{r-h}{r}\right)$	$\theta = 2\arccos\left(\frac{r-h}{r}\right)$
3	circular segment area	$K = \frac{r^2(\theta - \sin\theta)}{2}$	$K = \frac{r^2(\theta - \sin\theta)}{2}$
4	arc length	$s = r \times \theta$	$s = r \times \theta$
5	flow area	$A = K$	$A = \pi r^2 - K$
6	wetted perimeter	$P_W = s$	$P_W = 2\pi r - s$
7	hydraulic radius	$R_h = \frac{A}{P_W}$	$R_h = \frac{A}{P_W}$

Figure 5. Hydraulic radius equations for pipe flow (https://www.ajdesigner.com/phphydraulicradius/hydraulic_radius_equation_pipe.php)

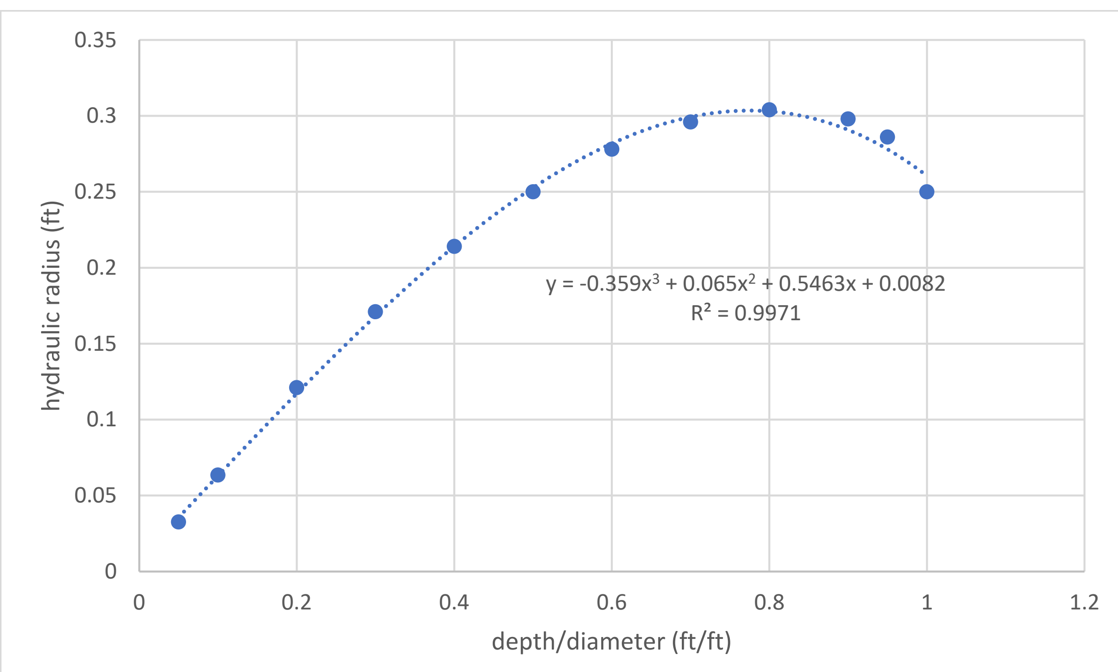


Figure 6. Hydraulic radius as a function of the fluid depth to pipe diameter ratio (rough estimate by regression).

The following is an example of the hydraulic calculations:

$Q = 35\ ft^3/sec$ (from WinSLAMM for the time increment being considered)

$D = 3$ ft diameter pipe

$S = 0.005$ ft/ft

$L = 300$ ft long pipe section

$n = 0.013$

The Manning's equation (and as shown on Figure 1) indicate that the full flowing pipe discharge value (Q_{full}) is 47 ft^3/sec. Therefore:

$Q/Q_{full} = 35/47 = 0.74$

From Camp's curve (and Figure 3), the corresponding depth to diameter ratio (d/D) is 0.73, and the actual depth is therefore 0.73* 3 ft = 2.2 ft. From Figure 4, the corresponding velocity to full flow velocity (V/V_{full}) is 0.97. For a 3 ft diameter pipe, the cross-sectional area is 7.1 ft^2 and the corresponding Vfull value is: (47 ft^3/sec)/7.1 ft^2 = 6.6 ft/sec. Therefore, the actual velocity is 0.97 * 6.6 ft/sec = 6.4 ft/sec. Similarly, the hydraulic radius is 0.30 ft. In summary:

$V = 6.6$ ft/sec

$R = 0.3$ ft

$d = 2.2$ ft

Particle Settling in Flowing Stormwater

The potential settling of stormwater particulates is dependent on the length of pipe, stormwater velocity, and depth of flow. The critical particle size (that which settles to the bottom of the pipe throughout its length) is calculated by dividing the flow depth (ft) by the travel time along the pipe (sec). This results in the settling rate of the critical particle size, with that size and larger (having greater settling rates) settling to the bottom of the pipe. The resulting travel time for the 300 ft example with a 6.6 ft/sec velocity would be: 300 ft/(6.6 ft/sec) = 45.5 sec. The corresponding critical settling time with a depth of 2.2 ft would be: 2.2 ft/45.5 sec = 0.048 ft/sec. Figure 7 is a plot of settling velocities for different sized particles with different specific gravities, while Figures 8 and 9 are rough regression estimates for 2.65 specific gravity particles (most stormwater particles are in the 1.5 to 2.5 specific gravity range). These plots use settling rates in cm/sec units. Therefore, (0.048 ft/sec) * (30.48 cm/ft) = 1.46 cm/sec. The corresponding critical particle size is therefore about 132 µm.

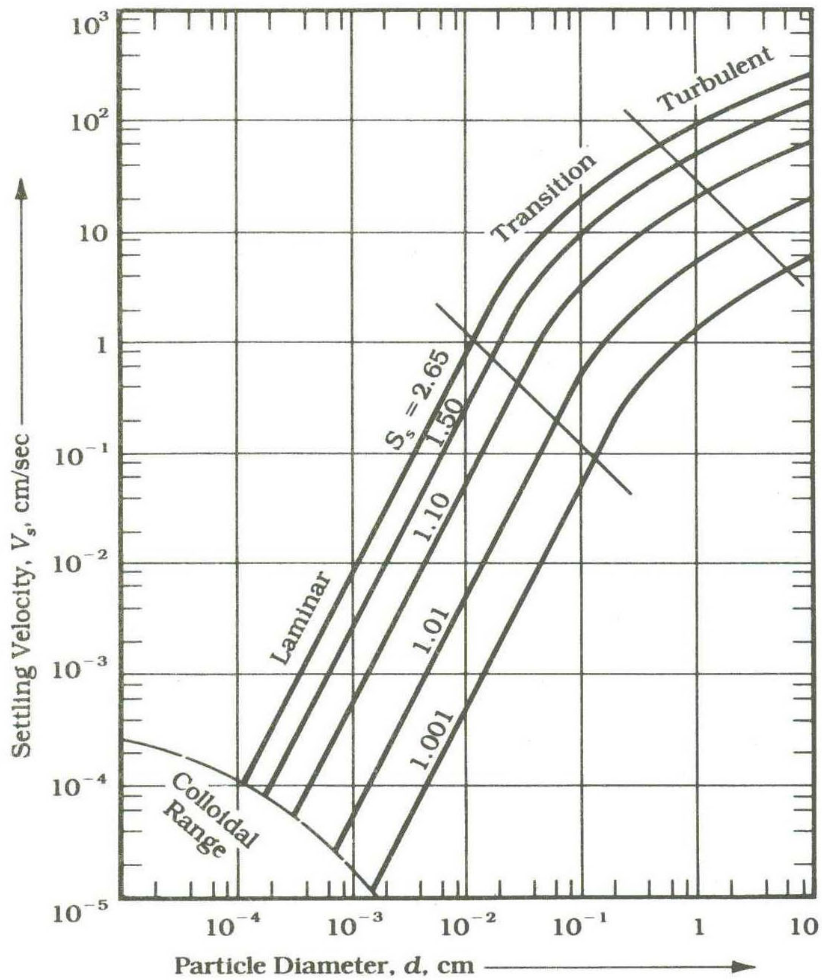


FIGURE 9.5 *Type I Settling of Spheres in Water at 10°C*

Adapted from "Water Treatment" by T. R. Camp in *Handbook of Applied Hydraulics*, 2nd ed. Edited by C. V. Davis. Copyright © 1952 by McGraw-Hill., Inc. Reprinted by permission.

Figure 7. Stokes (laminar) and Newtons (turbulent) settling of particles for different particle sizes and specific gravities.

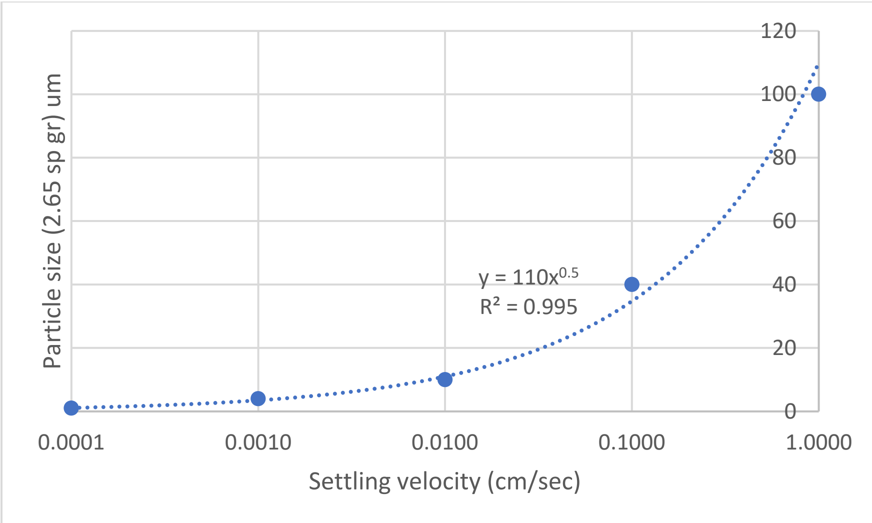


Figure 8. Plot illustrating critical particle size vs. settling velocity (2.65 specific gravity).

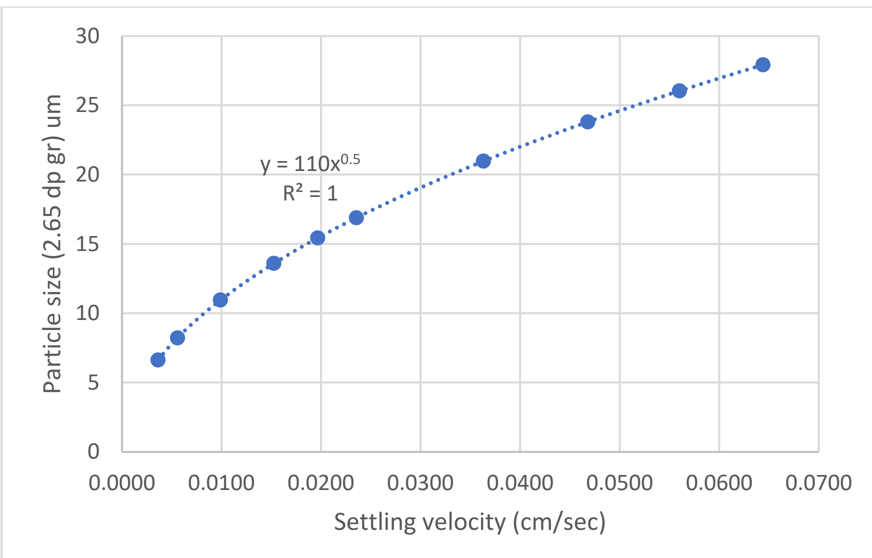


Figure 9. Settling characteristics for small particles (<25 µm) (2.65 specific gravity).

When designing storm drainage systems, a minimum water velocity of 3 ft/sec is usually used to prevent excessive sedimentation in the system. The above example indicates a flow rate of more than twice that criterion, so sedimentation is unlikely, due to the shear stress of the flow water. However, most stormwater drainage systems receive influent flows throughout their length, with much less flow in the upper reaches of the system (and with corresponding smaller pipes to result in higher "self-cleaning" velocities). There are usually minimal pipe diameters specified for storm drainage (usually 18 inches) to allow access for cleaning and to minimize clogging with large debris. This usually results in sedimentation at least in upper reaches of storm drainage systems, if the slopes cannot be increased to result in higher flow rates. Figure 10 shows how the velocity decreases as the depth of flow decreases. The depth would need to be less than about 7 inches deep in the 3 ft diameter pipe for velocities less than 3 ft/sec. Besides occurring in upper reaches in the storm drainage system, these low velocities would also occur as the stormwater entering the drainage system decreases as the storm abates and the remaining flows from the watershed enter the system at the end of the storm.

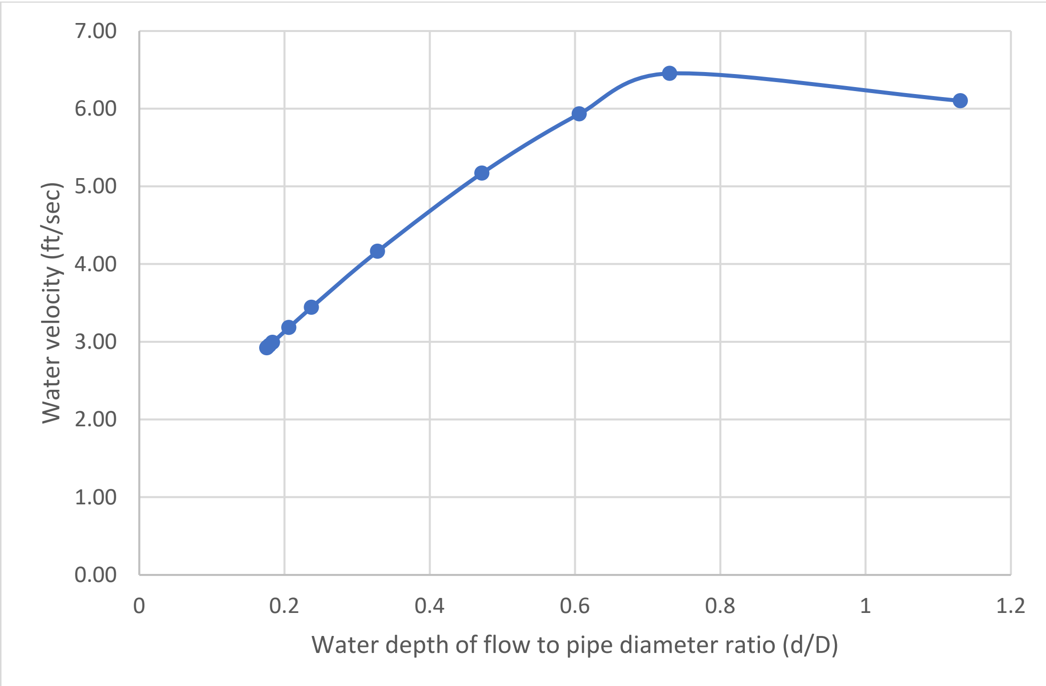


Figure 10. Water velocity vs. depth of flow in 3 ft pipe at 0.005 ft/ft slope.

“Safe” channel velocities and associated shear stress have long been published to protect natural channels from active erosion. Table 1 is an example which shows 2 to 3 ft/sec as the maximum safe (non-eroding) velocity for silt loams, for example. Shales and hardpans have safe velocities of 6 ft/sec. These values are similar to those used for “self-cleaning” velocities in stormwater and sanitary drainage systems, as noted previously.

Table 1. Maximum Permissible Velocities and Corresponding Unit Tractive Force (Shear Stress) (U.S. Bureau of Reclamation research, Fortier and Scobey 1926)

		Clear Water		Water Transporting Colloidal Silts	
Material	n	V (ft/sec)	τ_o (lb/ft^2)	V (ft/sec)	τ_o (lb/ft^2)
Fine sand, colloidal	0.020	1.50	0.027	2.50	0.075
Sandy loam, noncolloidal	0.020	1.75	0.037	2.50	0.075
Silt loam, noncolloidal	0.020	2.00	0.048	3.00	0.11
Alluvial silts, noncolloidal	0.020	2.00	0.048	3.50	0.15
Ordinary firm loam	0.020	2.50	0.075	3.50	0.15
Volcanic ash	0.020	2.50	0.075	3.50	0.15
Stiff clay, very colloidal	0.025	3.75	0.26	5.00	0.46
Alluvial silts, colloidal	0.025	3.75	0.26	5.00	0.46
Shales and hardpans	0.025	6.00	0.67	6.00	0.67
Fine gravel	0.020	2.50	0.075	5.00	0.32
Graded loam to cobbles when noncolloidal	0.030	3.75	0.38	5.00	0.66
Graded silts to cobbles when noncolloidal	0.030	4.00	0.43	5.50	0.80
Coarse gravel, noncolloidal	0.025	4.00	0.30	6.00	0.67
Cobbles and shingles	0.035	5.00	0.91	5.50	1.10

Note:
• an increase in velocity of 0.5 ft/sec can be added to these values when the depth of water is greater than 3 ft.
• a decrease in velocity of 0.5 ft/sec should be subtracted when the water contains very coarse suspended sediments.
• for high and infrequent discharges of short duration, up to 30% increase in velocity can be added

Fortier, S. and F.C. Scobey. "Permissible canal velocities." *Trans. ASCE*, Vol. 89, paper No. 1588, pp. 940-984. 1926.

Shear stress is now more commonly used to predict sediment movement. The following equation is used to calculate shear stress in flowing water: $\tau_0 = \gamma RS$
where: τ_0 is shear stress (lb/ft^2)
ϒ is the specific weight of water (62.4 lbs/ft^3)
R is the hydraulic radius (the area divided by the wetted perimeter), and
S = hydraulic gradient (ft/ft)

note, 1.00 lb/ft^2 = 47.9 Pa

Figure 11 is a plot of allowable tractive force (shear stress) vs. sediment particle sizes that reflect the carrying capacity of the flowing water. This plot is similar to Table 1, which shows that the allowable water velocities (and shear stress values) increase for water carrying silts compared to clear water. Figure 12 is a rough regression estimate for water with a high content of fine sediment for a shear stress range of 3.7 to 9 Pa. Flowing water with a shear stress less than 3.7 Pa have a critical particle size of 100 µm; particles smaller than 100 µm would be carried with the water, while larger particles would settle (depending on their settling velocities, water velocity, and length of pipe). Shear stress values greater than 9 Pa could still mobilize large particles of about 5 mm and larger.

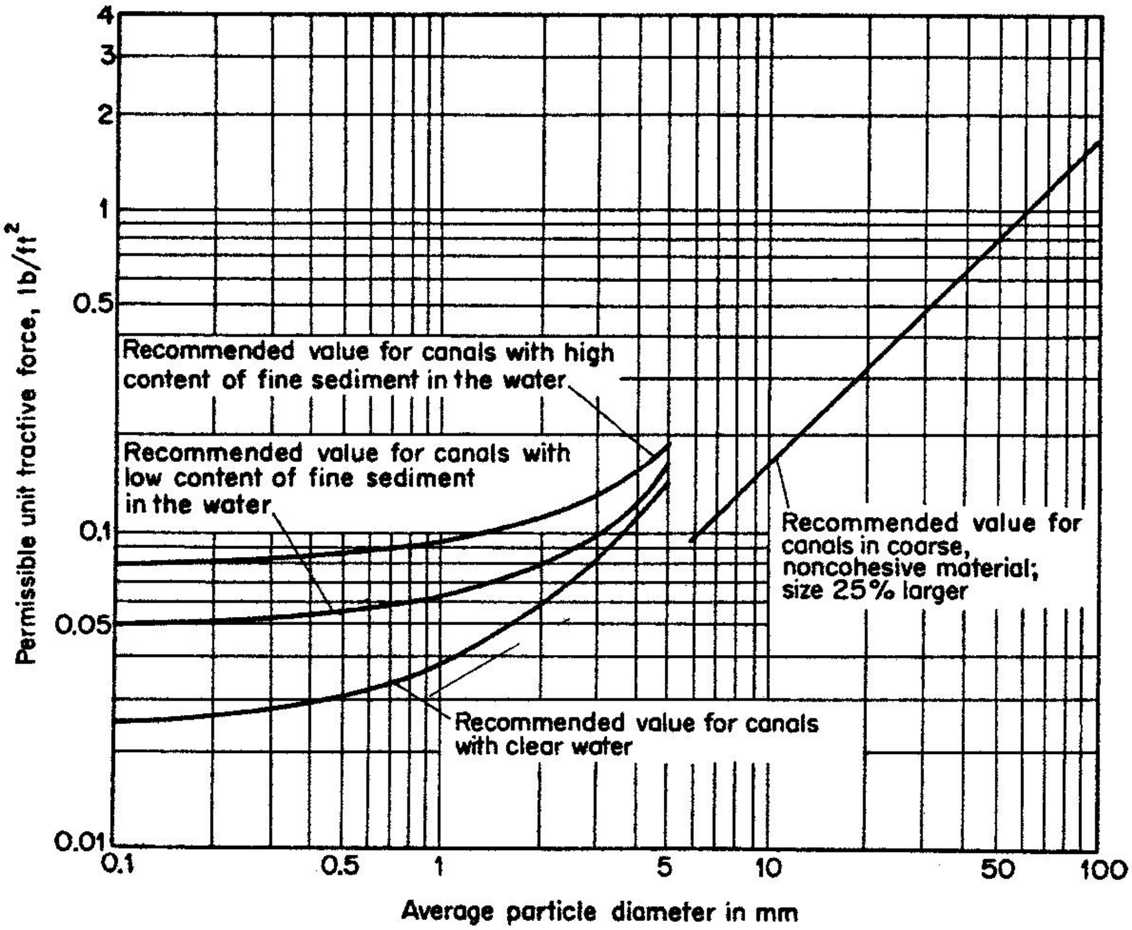


Figure 11. Allowable shear stresses (tractive forces) for canals in granular materials (U.S. Bureau of Reclamation, reprinted in Chow 1959).

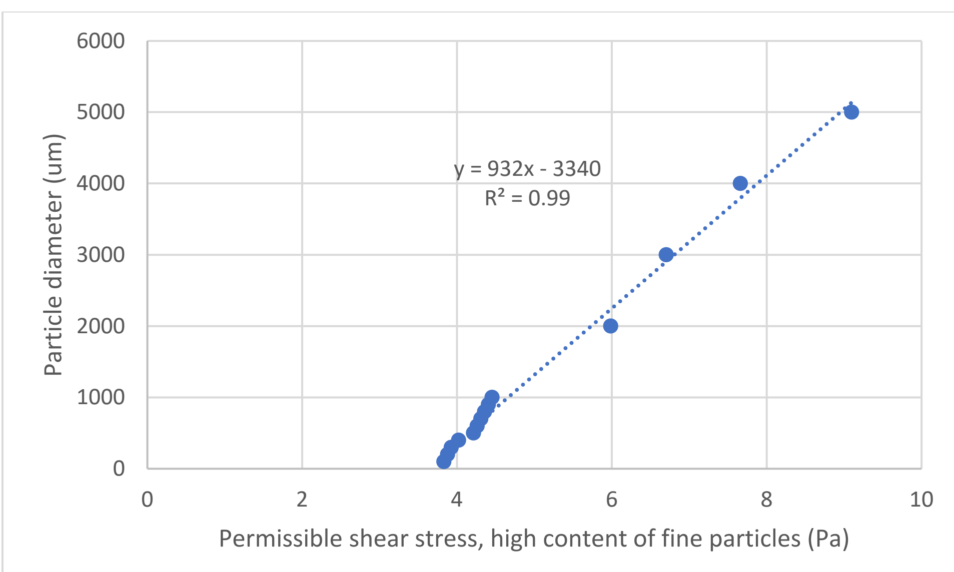


Figure 12. Allowable shear stress for water with high content of fines (100 µm if Pa<3.7 and n/a for Pa>9) (rough regression estimate).

Scour of Sediment by Flowing Stormwater

Figure 13 is a plot of allowable shear stress for different particle sizes, showing initial suspension and initial motion limits for discrete particles. Particles larger than the initial motion value are generally stable, particles between the initial suspension and initial motion values may move as bedload, while particles smaller than the initial suspension value would likely be resuspended.

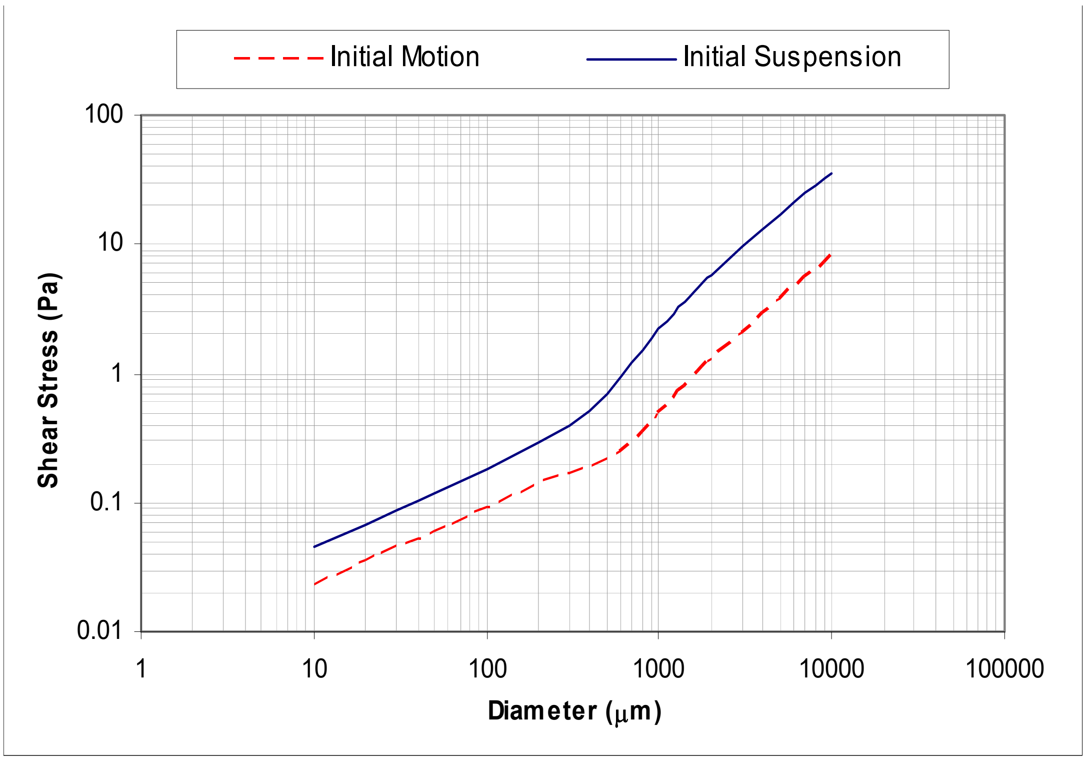


Figure 13. Scour potential (stable bed if lower than initial motion critical value; moving bed load if between initial motion and initial suspension values; resuspended/scour if above initial suspension value). Cheng-Chiew Criteria 1999.

Figures 14a and 14b show rough regression estimates for initial suspension particle sizes for low (Pa < 1) and high (Pa > 1) shear stress conditions. Figures 15a and 15b are similar plots for initial motion particle sizes for low (Pa < 0.5) and high (Pa > 0.5) shear stress values.

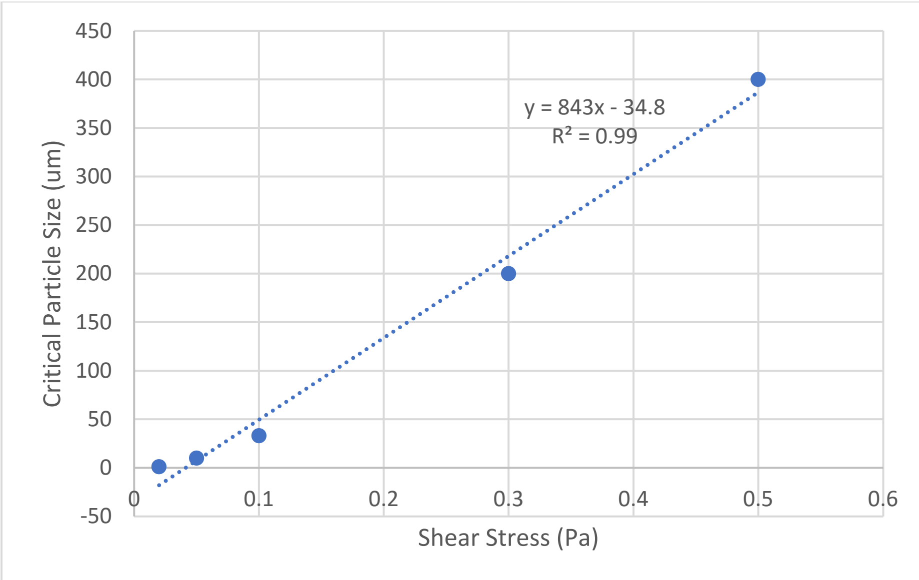


Figure 14a. Initial suspension for low shear stress (Pa<1) (rough regression estimate).

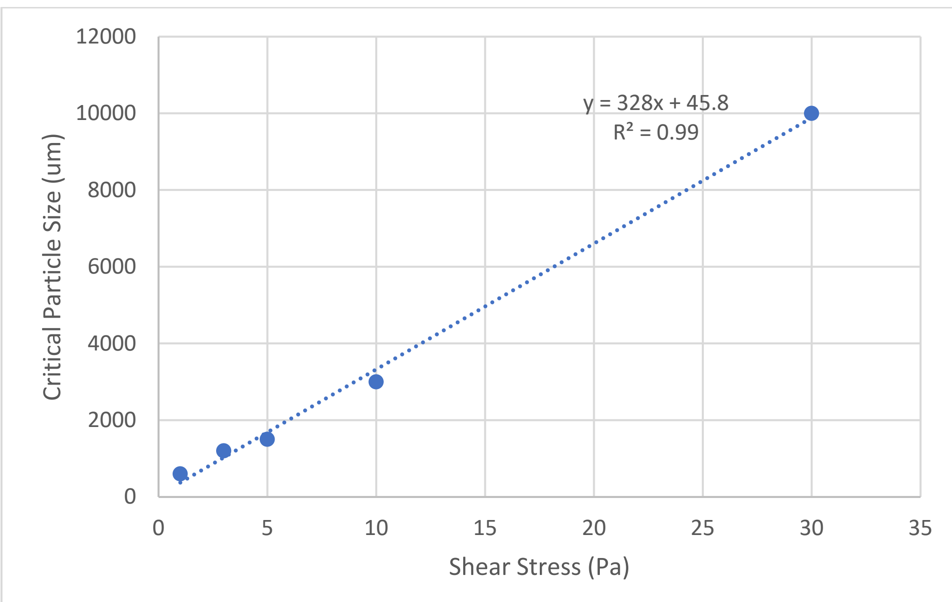


Figure 14b. Initial suspension for high shear stress (Pa>1) (rough regression estimate).

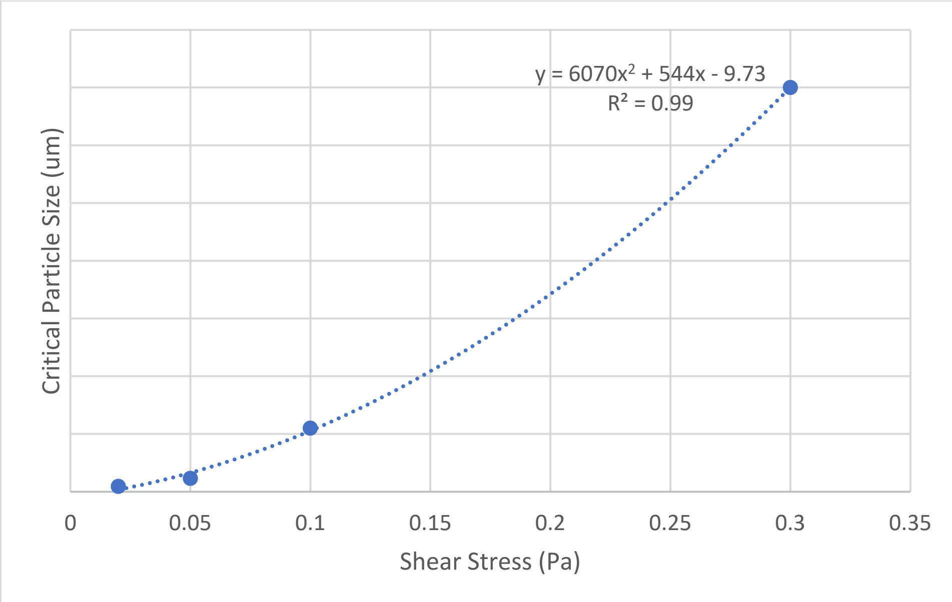


Figure 15a. Initial motion for low shear stress (Pa<0.5) (rough regression estimate).

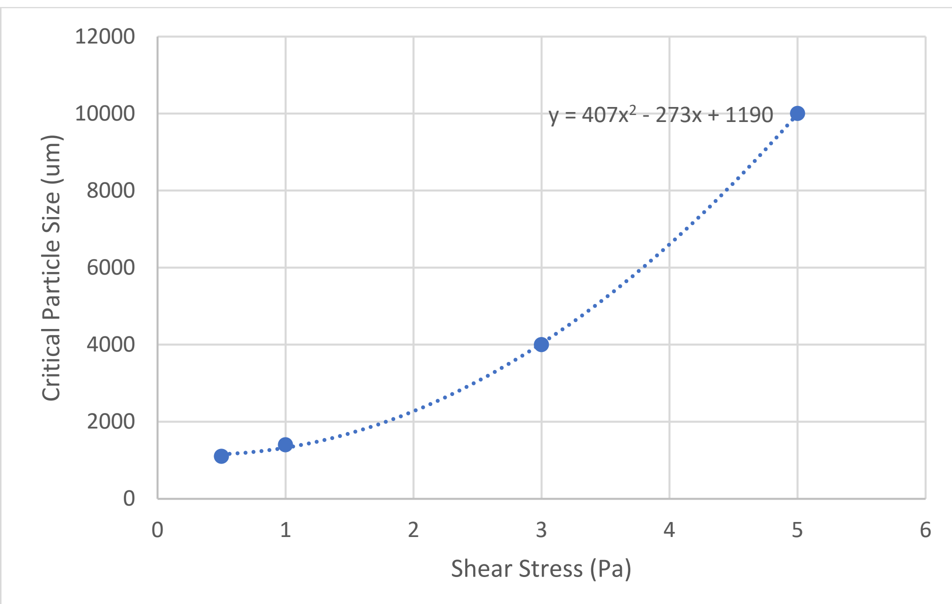


Figure 15b. Initial motion for high shear stress (Pa>0.5) (rough regression estimate).

When the flow reduces near the end of the storm event, small particles, including clays and fine silts will accumulate in the storm drainage system. Between events, with no flows, these cohesive small particles become more difficult to scour, especially as they become compacted (low void ratios). Figure 16 is a plot showing the shear stress (shown as unit tractive force) necessary to scour cohesive fine materials. Figure 17 is a rough regression estimate of the shear stress required to scour these materials.

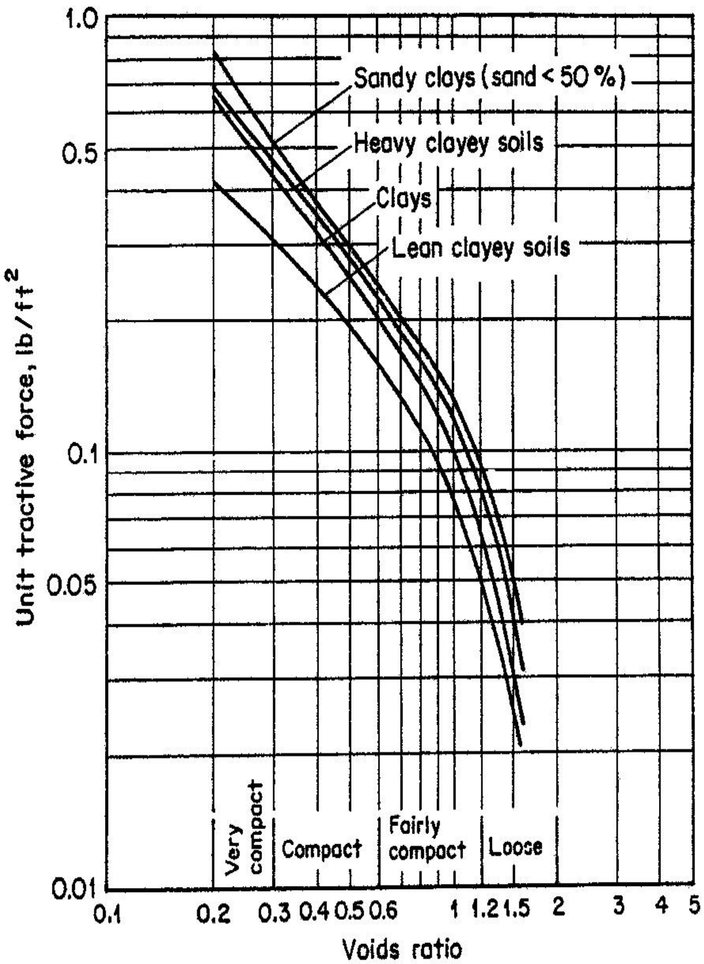


Figure 16. Shear stress (unit tractive force) and movement of cohesive deposits (COE 1994).

U.S. Army Corps of Engineers (COE). *Engineering and Design: Channel Stability Assessment for Flood Control Projects*. EM 1110-2-1418. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. 1994.

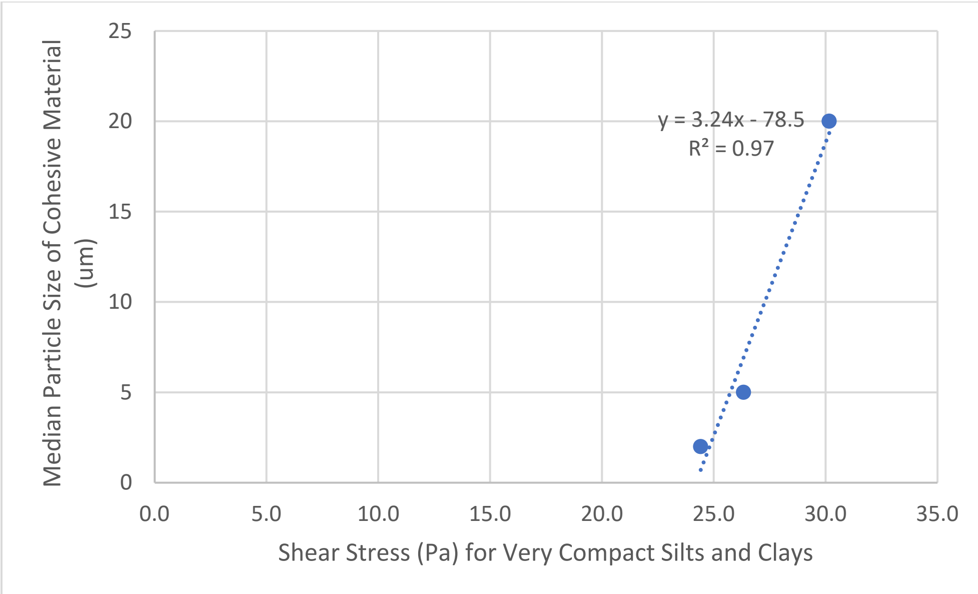


Figure 17. Shear stress and movement of cohesive very compact clays and silts (rough regression estimate).

Therefore, at least 0.5 lb/ft2 (24 Pa) is required to scour of even the smallest clay for very compact materials and >0.65 lb/ft2 (>31 Pa) is required to scour 20 µm materials (upper limit for cohesive material). These shear stress values are quite large and would rarely be expected, except during large discharges approaching the design limits with moderate to steep slopes.

Summary

Figure 18 shows plots of sediment stability for different water depth to pipe diameter conditions for an example 3 ft pipe at 0.005 ft/ft slope. Particles smaller than about 100 µm will remain suspended during most flows. As the flows subside, even these particles will settle. However, these particles (up to about 1,000 µm for this example) may remain suspended during most flows due to the shear stress, with the larger particles contributing to bedload (up to about 5,000 µm for this example) and the largest particles forming a stable sediment layer. During subsequent events, it is likely that most of the small particles that settled during the abating flows of prior events, will be resuspended during moderate to high flows, with the exception of cohesive clays and fine silts (<20 µm) that require substantial shear stress to erode. Therefore, it is likely that long-term sediment in the pipe will be comprised of cohesive material (<20 µm) and very large material (>1,000 µm), along with other material trapped under a protective layer of stable large particles.

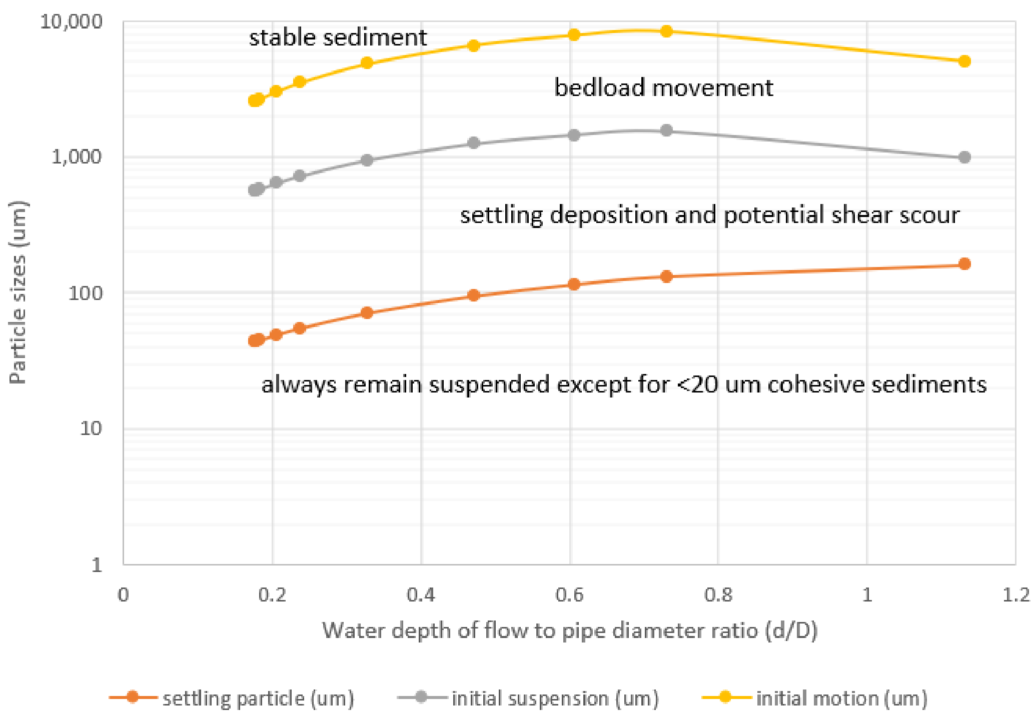


Figure 18. Settling and resuspension potential (300 ft long, 3 ft diameter pipe at 0.005 ft/ft slope).

The suggested analytical strategy for calculating sedimentation and scour/resuspension of stormwater particulates in pipes is the following:

1. Sedimentation is calculated based on travel time and depth of flow to obtain the critical particle size that will remain suspended with larger particles settling in the pipe. This is compared to:

    a. The carrying capacity of the flowing water with high content of fines depends on the shear stress. For low shear stress (Pa < 3.5), the critical particle size is about 100 µm (only sizes smaller will be transported in the water, with larger sizes able to settle). Shear stress values of Pa = 4.5 correspond to a 1mm particle carrying capacity, while for larger shear stresses (Pa > 9) there is no restriction for the full range of particles in stormwater. Particles smaller then the critical size calculated by the carrying capacity of the flowing water will remain suspended, while larger particles will be deposited (if the settling calculations indicate settling for the water velocity, depth of flow, and length of pipe.

2. Scour of previously deposited material will lead to resuspension of particles smaller than indicated by the initial suspension/erosion shear stress, based on hydraulic radius and pipe slope. Smaller particles would be resuspended and flow with the stormwater, while larger particles that are smaller than the initial motion particles, would move as bedload:

a. Initial motion is also due to shear stress. Particles larger than those predicted by initial motion would remain fixed in the sediment, while those smaller (but larger than initial suspension) would move as bedload.

3. Scour of cohesive sediment (<20 µm silts and clays) may occur, depending on the calculated shear stress. For very compact cohesive sediment (which occurs between events with drying of these fine sediment materials), only unusually high subsequent flows would have sufficient shear stress to scour these sediments. These very small particles would not settle during normal stormwater flowing conditions, as the shear stress and carrying capacity would easily keep them suspended. However, after the rainfall ends, the inlet water discharges start to decrease as the watershed drains. Clays and fine silts would then settle if the settling calculation (settling velocity and length of pipe) indicates for these very low flows and shallow depths of flow in the pipes.