APPENDIX A

FORMULAE AND SAMPLE CALCULATIONS

Pipe Installation (Fused)

The fused polyethylene (PE) pipe can be pulled by a cable attached to a pulling head fastened to the pipe. This prevents damage to the PE pipe. The length of the fused pipe which can be pulled will vary depending upon field conditions and ease of access to the area. In general, the maximum pulling length for small diameter pipe, 12 inch and smaller, is normally limited to 1000 feet, and for larger pipe, about 500 feet. Longer lengths have been pulled, however, all conditions must be determined. The various pulling forces and lengths information is desirable for design and estimating purposes. The maximum force that can be applied to a pipe on level ground can be determined by the following formula:

$$P_t = (s_{max})\,A \qquad (1)$$

Where P_t = maximum pulling force (lb)

s_{max} = maximum allowable tensile stress, 1000 psi

A = cross sectional area of pipe, in^2

Note: HDPE primary properties are specified by cell classification per ASTM D 3350. Tensile strength is normally cell class 4 which is 3000 to 3500 psi. The allowable tensile stress of 1000 psi provides a design factor of approximately 3 to compensate for installation stresses.

The following formula can be used to determine the pulling length:

$$L = \frac{Pt}{fa}$$

Where L = pulling length (feet)

f = friction coefficient (0.5)

Sample Calculations:

1. 1000 feet of 12 inch, SDR 26 is being pulled over smooth ground with a 5^o slope. What is the pulling force?

   $t = 0.490$ inches $d = 12.75 - 0.49 = 12.26$ $C = Bd$

   $A = Cxt = p \times 12.26 \times 0.49 = 18.87\ in^2$

   $P_t = 1000 \times 18.87 = 18{,}870$ lbs.

Pipe weight per foot:

$V = A \times 12 = 18.87\ (12) = 226.44\ in^3$

Weight $= 226.44\ (0.955)\ 0.0361 = 7.8$ lbs/ft

The maximum straight line of pipe that should be pulled (assuming $f = 0.5$) is:

$$L = \frac{18{,}870}{0.5\ (7.8)}$$

$L = 4838$ feet

Note: The maximum radius of curvature should be limited to maximum axial strain properties of the pipe, as discussed below.

Longitudinal Bending (Fused)

Bending induced during the insertion step in transporting pipe lengths from assembly sites to job sites, or permanent bends to accommodate line or grade changes should be limited to radii equivalent to a longitudinal strain recommended by the pipe manufacturer. The minimum allowable radius of curvature for any size and weight of pipe can be closely approximated from the following equation:

$$R_c = \frac{D_o}{2\, e_a} \qquad (3)$$

Where:

R_c = radius of curvature, in.

D_o = outside diameter of inserted pipe, in.

e_a = allowable axial strain = 1%

This equates to:

$$R_c = \frac{D_o}{2(0.01)} = \frac{D_o}{0.02} = 50\, D_o$$

Note: The allowable axial strain has a design factor of at least 3, however, the manufacturer should be consulted regarding their recommended long term allowable strain.

Insertion Trench (Fused)

The minimum length of the trench from which the fused polyethylene pipe is inserted into the existing pipeline to be rehabilitated can be calculated as a function of the pipe invert depth from ground surface, H and the permissible bend radius using the equation:

$$L \ \$ \ [H\,(2R-H)^{1/2} \qquad (4)$$

R = 50 or greater times PE pipe D_o or

$$R = 50\, D_o \qquad (5)$$

See figure A1 for pit trench configuration

EXAMPLE:

PE pipe D_o = 24.00 inches
Height of cover, H = 12 feet

R = 50 (24) = 1200 inches (100 feet)

$L \; \$ \; [12 (2 \text{ x } 100 - 12)]^{1/2} = [12 (188)]^{1/2}$
$L \; \# \; [2256]^{1/2} = 47.50$ Use 48 feet

Pipe Installation (Gasketed)

The gasketed pipe joint segments can be pushed and/or pulled into the existing pipeline from an insertion pit. The pipe joints should be inserted with spigot end first and the bell end trailing. The push/pull bearing plate should be applied against the flat surface of the bell step, to avoid damaging the bell, especially on plastic pipe (HDPE). The maximum pushing and/or pulling length is determined by the longitudinal compressive strength of the pipe and this varies with type of material and its design.

The access pit should be approximately 5 to 10 feet longer than the standard 20 foot pipe segment lengths. The width of the pit should be 2 to 4 feet wider than the diameter of the existing pipe.

In general, the maximum push/pull lengths for 18-inch and larger slipliner pipe is normally limited to 1000 feet in a dry sewer and about twice that in an active flowing sewer.

The existing pipeline condition, i.e., alignment and grade changes, structural and corrosion conditions, etc., must be determined prior to the installation. The maximum push/pull force to be applied can be determined by the following formula.

$$P_c = s_{max} A \qquad (6)$$

P_c = maximum push/pull force, lbs.

s_{max} = maximum allowable compressive stress psi

A = cross sectional area* of pipe, in^2

* located at minimal cross section

From Roark, axial compressive stress, psi

$$s_{max} = \frac{0.3\,Et}{r(SF)} \qquad (7)$$

E = use initial tensile or compressive modulus

t = minimum wall thickness, in.

r = mean radius, in

SF = Safety Factor usually 2.0 - 4.0 (for materials)

The following formula can be used to determine the push/pull length.

$$L = \frac{P_c}{fa\,(SF)}$$

Where L = estimated push/pull length (feet)

f = friction coefficient (= 0.5 in dry & = 0.25 in wet)

a = pipe weight (lbs/ft)

SF = 2.0 (for installation)

Sample Calculation:

1. Determine the estimated force needed and length of 36-inch inner profile wall HDPE pipe (RSC 160) that can be pushed/pulled through a dewatered (dry) 42-inch RCP pipeline. Pipe weighs 42 lbs/ft. Zbar = 0.797

D_o = 39.44 in   I = 0.277   I = $t^3/12$ t = 1.492 in.

$$s_{max} = \frac{0.3\ Et}{r(SF)}$$

E = 113,000 psi

t = 1.492 in (effective)

r = (39.44 - 1.49) / 2 = 18.975 in.

SF = 2.0

$$s_{max} = \frac{0.3\ (113{,}000)\ 1.492}{18.975\ (2.0)} = 1333 \text{ psi}$$

Force needed:

$$P_c = {}^{F}{}_{max}\ A$$

s_{max} = 1333 psi, A = B dt = B (37.492) 1.492 = 175.73

P_c = 1333 (175.73) = 234,248 lbs

$$L = \frac{234{,}248}{0.5\ (42)\ (2.0)} = 5578 \text{ Ft.}$$

2. Determine the estimated force needed and length of 36-inch diameter exterior profile wall HDPE pipe (RSC 160) that can be pushed/pulled through a dry 42-inch RCP. Pipe weighs 42 lbs/lf.

From Roark

$$\text{Axial Compressive Stress} = \frac{0.3\ E\ t}{r\ (SF)}$$

E = 113,000 psi (initial tensile modulus)
t = 0.36 inches (wall thickness raceway)
SF = 2, r = (36 + 0.36) / 2 = 18.18 inches

$$\text{Axial Comp. Stress} = \frac{0.3\ (113{,}000)\ 0.36}{18.18\ (2)} = 336 \text{ psi}$$

From Formula (6)

$$P_c = 336\ (\pi \times 36.36 \times 0.36) = 13.817 \text{ lbs.}$$

The profile wall does not make contact along its entire surface. Adjusted friction values are: f = 0.3 (dry) and f = 0.1 (wet). When using HDPE Pipe, the normal friction factors should be used, i.e., f = 0.5 and 0.25.

From Formula (7)

$$L = \frac{13{,}817}{0.25\ (42)\ (2)} = 658 \text{ feet}$$

3. Sample Calculation:

Determine the estimated force needed and length of 36-inch RPM pipe that can be pushed/pulled through a dry 42-inch RCP. The axial compressive stress of the RPM pipe is 14,000 psi. The pipe stiffness is 36 psi having a wall thickness of 0.72 inches.

Pipe weighs 71 lbs/lf.

D_o = 38.3 inches, t = 0.72, Effective t = 0.45 inches

From Formula (6)

$$P = 14{,}000\ (\pi \times 37.4 \times 0.45)$$
$$P = 740{,}222 \text{ lbs (w/o SF) and}$$
$$P = 185{,}055 \text{ lbs (w/4 to 1 - SF) Force used}$$

From Formula (7)

$$L = \frac{185{,}055}{0.5\ (71)\ (2)} = 2606 \text{ feet - length}$$

Hydrostatic Loads

When there is a possibility of groundwater level above the pipe, the level and its duration should be estimated, and pipe of sufficient wall thickness to withstand the pressure, without collapsing, should be used. It should be noted that an appropriate safety factor of 2 should be used. The following basic equation should be used to determine needed wall thickness:

$$P = \frac{24\ E_a\ I}{(1-\mu^2)d^3(FS)} \qquad (8)$$

P = pressure due to head of water, psi

E_a = apparent (time-corrected) modulus, psi

d = mean diameter, inches

μ = Poisson ratio

FS = Safety Factor (normally 2.0)

Note: Formula (8) is taken from Timoshenko/Von Mises

In order to determine needed wall thickness:

$$P = \frac{2E_a\ (t)^3}{(1-\mu^2)\ (d)^3\ (FS)} \qquad (9)$$

$$t = \frac{[P(1-\mu^2)\ d^3 (FS)]^{1/3}}{[2\ E_a]^{1/3}} \qquad (10)$$

Formula (8-10) applies primarily to solid wall pipe, such as, High Density Polyethylene, Polyvinyl Chloride, Steel Pipe, Ductile Iron Pipe and CIPP (See note below).

Note: CIPP is Cured-in-Place-Pipe (Epoxy resin)

The following mathematical modification of Formula (9) may be used when utilizing the dimensional ratio (DR).

$$P = \frac{2\ E_a}{(1-\mu^2)\ (DR-1)^3\ (FS)} \qquad (11)$$

In order to determine needed dimensional ratio:

$$(DR-1)^3 = \frac{2E}{(1-\mu^2)\ P\ (FS)}$$

$$DR = \left[\frac{2E_a}{(1-\mu^2)\ P\ (FS)}\right]^{1/3} + 1 \qquad (12)$$

Note: Apply an appropriate Safety Factor (normally 2.0)

The following product material Poisson ratios should be used:

Material	Poisson Ratio
HDPE	0.45
PVC	0.38
RPM	0.30
CIPP	0.30
Steel	0.30
DIP	0.30

The following product material initial flexural modulus (E_i) values should be modified for apparent long term values (E_a):

Material	E_i (Initial-psi)
HDPE	113,000
PVC	400,000
RPM	1.5×10^6
CIPP	300,000
Steel	30×10^6*
DIP	24×10^6*

* Initial and long term assumed to be the same.

When slipliner pipe is subjected to a constant on-going loading, the following apparent modulus values should be used.

Material	E_a (long term - psi)*
HDPE	24,000
PVC	113,000
RPM	0.75×10^6
CIPP	150,000
Steel	30×10^6**
DIP	24×10^6**

* Long term values set at 50 years, determine by long term stress regression testing.

** The wall thickness should be increased for corrosion allowance, usually 0.08 inch or greater.

Note: The manufacturer's long term Modulus values must be obtained through acceptable long term testing.

Restrained Hydrostatic Loads

When the annulus between the slipliner pipe and the existing pipe to be lined exceeds one inch, it is recommended that this space be grouted. This grout, when set, provides restraining support for the slipliner pipe. Research has determined that this support enhances the buckling resistance by at least six times that without the grout. The hydrostatic buckling can be determined by using the following adjusted formula:

$$P = \frac{2\,K\,E_a\,t^3}{(1-\mu^2)\;d^3\,(FS)} \qquad (13)$$

$$t = \frac{[\,P\,(1-\mu^2)\,d^3\,(FS)]^{1/3}}{[2KE_a]^{1/3}} \qquad (14)$$

$$P = \frac{2K\;E_a}{(1-\mu^2)\,(DR-1)^3\,(FS)} \qquad (15)$$

$$DR-1 = \frac{[\,2\,K\,E_a\,]^{1/3}}{[\,(1-\mu^2)\,P(FS)]^{1/3}} \qquad (16)$$

K = grout support factor
K = 7 (CIPP)
K = 6 all other pipes

Grout the annular space between the OD of the installed liner pipe and the ID of the existing pipe with a cement or chemical based grout. During the grout placement, assure that the safe grouting pressure given below is not exceeded.

Safe grouting pressure (psi) = pipe stiffness (PS-psi)) FS

$$P_g = \frac{24\,E_i\,I}{(1-\mu^2)d^3} = \frac{2\,E_i\,t^3}{(1-\mu^2)\,d^3} \qquad (17)$$

P_g = Safe Grouting pressure (psi)

E_i = Initial modulus

From ASTM D-2412

$EI = 0.0186\,(PS)d^3$

$$PS = \frac{E_i\,I}{0.0186\,d^3} \qquad (18)$$

$$\frac{E_i\,I}{d^3} = 0.0186\,PS \qquad (19)$$

$$P_g = \frac{24\,(0.0186)\,PS}{(1-\mu^2)} = \frac{0.446\,PS}{(1-\mu^2)} \qquad (20)$$

Refer to material ratio table for the following calculation examples. It is recommended that a factor of safety of at least 1.5 be applied to the grouting pressures.

Material	**Poisson Effect**	**FS Effect**
HDPE	0.558 PS	0.37 PS
PVC	0.519 PS	0.35 PS
RPM	0.491 PS	0.33 PS
Steel	0.491 PS	0.33 PS
DIP	0.491 PS	0.33 PS

Useful approximate conversion relationships are as follows:

Dimensional ratio (DR) to pipe stiffness (PS)

$$PS = \frac{4.47\,E_i}{(DR-1)^3} \qquad (21)$$

Ring Stiffness Constant (RSC) to pipe stiffness (PS)

$$PS = \frac{6\,(RSC)}{D} \qquad (22)$$

Safe grouting pressure (P_g) = FS Effect

Sample Calculations

1. A 36-inch solid wall HDPE pipe sliplined into an existing 42-inch RCP pipe. The pipe is 20 feet deep with 10 feet of groundwater over the pipe. Check the adequacy of the pipe for hydrostatic loading.

   Try an SDR 32.5. The pipe is 36.00 inches OD having a wall thickness of 1.108 inches.

   d = 36.00 - 1.108 = 34.892 in.

   E_a = 24,000 psi

From Formula (11)

$$P = \frac{2\,(24{,}000)}{(1-0.45^2)\,(32.5-1)^3} = \frac{48{,}000}{(0.80)\,(31{,}256)} = 1.92 \text{ psi}$$

It is suggested that a Safety Factor of 2 be used.

$$P = \frac{\text{Allowable}}{2} = \frac{1.92}{2} = 0.96 \text{ psi}$$

This equates to 2.22 feet of groundwater hydrostatic head.

The pipe strength will not prevent long term collapse. It is necessary to grout annular space or use a stiffer pipe. Grouting annular space provides approximately 6 times more buckling resistance.

P = 2.22 x 6 = 13.32 feet - This is acceptable.

Grouting is preferred due to several other viable reasons. (See F 950)

Safe grouting pressures are:

From Formula (21)

$$PS = \frac{4.47\,(113{,}000)}{(31.5)^3} = 16.16 \text{ psi (initial)}$$

From Formula (20) including adjustment effects.

P_g = 0.37 (16.16) = 5.98 or 6 psi

A 36-inch inner profile wall HDPE pipe sliplined into an existing 42-inch RCP pipe. The pipe is 20 feet deep with 10 feet of groundwater over the pipe.

Try an RSC 100. The pipe is 36.00 inches I.D., having an $I = 0.277$ $in^4/in.$ and an effective wall thickness of 1.493 inches. The centroid of the section is $Z = 0.7965$.

$d = D_i + 2Z = 36 + 2\ (0.7965) = 37.593$ inches

D_i is inside diameter

From Formula (8)

$$P = \frac{24\ (24{,}000)\ 0.277}{(0.80)\ (37.593)^3} = 3.75 \text{ psi}$$

Use a FS = 2.0

$$P = \frac{3.75\ (2.31)}{2.0} = 4.33 \text{ ft.}$$

The pipe strength will not prevent long term collapse. it is necessary to grout annular space or use a stiffer pipe. Grouting annular space provides approximately 6 times more buckling resistance.

From Formula (22)

$$PS = \frac{6\ (100)}{36} = 16.67 \text{ psi (initial)}$$

From Formula (20) including adjustment effects

$P_g = 0.37\ (16.67) = 6.17$ psi

It should be noted that the maximum OD of the liner pipe must be less than the ID of the existing pipe and also meet its alignment. The selected liner wall is H=1.593 inches.

OD = 36 + 3.186 = 39.186 inches (ok)

3. A 36-inch RPM pipe sliplined into an existing 42-inch RCP pipe. The pipe is 20 feet deep with 10 feet of groundwater over the pipe.

Try a PS of 36 psi. Pipe is 38.30 inches OD having wall thickness of 0.72 inches.

$d = 38.30 - 0.72 = 37.58$ in.
$E_a = 750{,}000$ psi

From Formula (9)

$$P = \frac{2\,(750{,}000)}{(1-0.3^2)}\ \frac{0.72^3}{37.58^3} = 11.59 \text{ psi}$$

Use a FS = 2.0

$$P = \frac{11.59\,(2.31)}{2.0} = 13.39 \text{ feet (ok)}$$

Grouting the annulus provides 6 times more buckling resistance. The safe pressure for grouting the annulus would be;

From Formula (20) including adjustment effects

$$Pg = 0.33\ PS = 0.33\,(36) = 12 \text{ psi}$$

It should be noted that the maximum OD of the liner pipe must be less than the ID of the existing pipe and also meet its alignment. The selected liner wall is 0.72 inches.

$$OD = 36.86 + 1.44 = 38.30 \text{ inches (ok)}$$

4. A 42-inch Cured-in-place-Pipe (CIPP) will be inverted into an existing 42-inch RCP pipe. The pipe is 20 feet deep with 10 feet of groundwater over the pipe.

Try a CIPP having a wall thickness of 0.75 inches. The method of placing CIPP inside the existing pipe wall negates the necessity for grouting the annular space. Therefore, Formulae (13) or (15) may be used directly for determining the buckling resistance.

From Formula (13)

$$P = \frac{2\,(7)\,150{,}000\,(0.75)^3}{(1 - 0.l3^2)\,(41.25)^3} = 12.84 \text{ psi}$$

$$P = \frac{12.84\,(2.31)}{2.0\,(FS)} = 14.83 \text{ ft. (ok)}$$

From Formula (15)

$$DR = \frac{42}{0.75} = 56$$

$$P = \frac{2\,(7)\;150{,}000}{(1 - 0.3^2)\,(56 - 1)^3} = 13.87 \text{ psi (check)}$$

Note: Can go to a thinner wall.

5. A 42-inch PVC Sewer Lining System (Danby) will be spirally erected into an existing 42-inch RCP pipe. The pipe is 20 feet deep with 10 feet of groundwater over the pipe.

Try the standard design profile. The initial modulus (E_a) is 420,000 psi and the long term modulus (E_{50}) is 140,000 psi. The profile moment of inertia (I) is 0.004 in^4/in.

The Timoshenko and Gere, "Theory of Elastic Stability" procedure will be used in this hydrostatic buckling analysis.

$$P = \frac{EI\,(k^2-1)}{R^3}$$

k = buckling node number

Other terms have been previously defined.

k = 2 for ungrouted material

Therefore:

$$P = \frac{3\,EI}{R^3} \quad \text{(prior to encorporation of safety factor)}$$

Man-Entry grouting normally provides 100% annulus filling. It will be assumed that the grouting in not perfect and that a 30^o void may be developed in the annulus. Two hinged concrete supports will provide a k factor equal to 17.18. (Timoshenko/Gere)

Then:

$$P = \frac{EI\,(17.18^2 - 1)}{R^3} = \frac{294\,EI}{R^3} \text{ or } \frac{2344\,EI}{D^3}$$

Use long term Modulus of Elasticity, E_{50}, for calculating the buckling resistance. The effective wall thickness is:

$$I = \frac{t^3}{12}, \quad t^3 = 12I, \quad t = (12I)^{1/3} \qquad I = 0.004$$

$$t = (12 \times 0.004)^{1/3} = (0.048)^{1/3} = 0.36 \text{ in.}$$

The mean diameter of the PVC liner is:

$$d = 42 - 0.36 = 41.74 \text{ in.}$$

From Formula (8):

$$P = \frac{2344\,(140{,}000)\,0.004}{0.91\,(41.74)^3\ 2} = 9.92 \text{ psi } (22.9 \text{ ft.})$$

This provides satisfactory long term buckling strength.

The effective pipe stiffness is:

$$PS = \frac{E_i\ I}{0.0186d^3} = \frac{420{,}000\,(0.004)}{0.0186\,(41.74)^3} = 1.24 \text{ psi}$$

Safe grouting pressure (P_g) = FS Effect

$$P_g = 0.35\,(1.24) = 0.43 \text{ psi}$$

This will be done by multi-stage careful grouting.

Flow Comparisons

The sliplining rehabilitation methods all reduce the remaining available waterway cross section for hydraulics. Plastic pipe manufacturers claim Manning flow characteristics at n = 0.010. This value has not been substantiated under long term sewer flow conditions, nor can they be attained except in laboratory conditions with extremely high Reynolds Numbers. Further, under field conditions actual "n" value for plastic pipes are for all practical purposes, the same as VCP and RCP. No reduction of "n" value shall be used for any material.

For comparative purposes, various rehabilitation methods are illustrated below showing relative performance for lining an existing 42-inch pipeline.

Material	**Inside Diameter (in.)**	**Flow Ratio**
HDPE (Solid Wall)	33.78	0.616
HDPE (Profile Wall)	36.00	0.730
RPM	36.86	0.777
CIPP	40.50	1.000 (Minimum reduction)

When gravity flow sewer pipes are half full, or full, the velocities are equal. The volume of flow in a half full sewer is 2 that of a full flow sewer. The flow ratio for the tabulated values above are based on pipe inside diameter to the 3/8 power. (Reference should be made to the NCPI Handbook)