Defining Parameters of Horizontal Directional Drilling :

$D_1 := 10.75\ in$	Pipe 1 outer diameter
$D_2 := 2.375\ in$	Pipe 2 outer diameter
$D_{rod} := 3.5\ in$	Assumed drill rod diameter
$DR_1 := 9$	Dimension ratio of Pipe 1
$DR_2 := 11$	Dimension ratio of Pipe 2
$T_{p1} := \frac{D_1}{DR_1} = 1.194\ in$	Thickness of Pipe 1
$T_{p2} := \frac{D_2}{DR_2} = 0.216\ in$	Thickness of Pipe 2
$C_1 := \pi \cdot D_1 = 33.8\ in$	Pipe circumference of pipe 1
$C_2 := \pi \cdot D_2 = 7.5\ in$	Pipe circumference of pipe 2

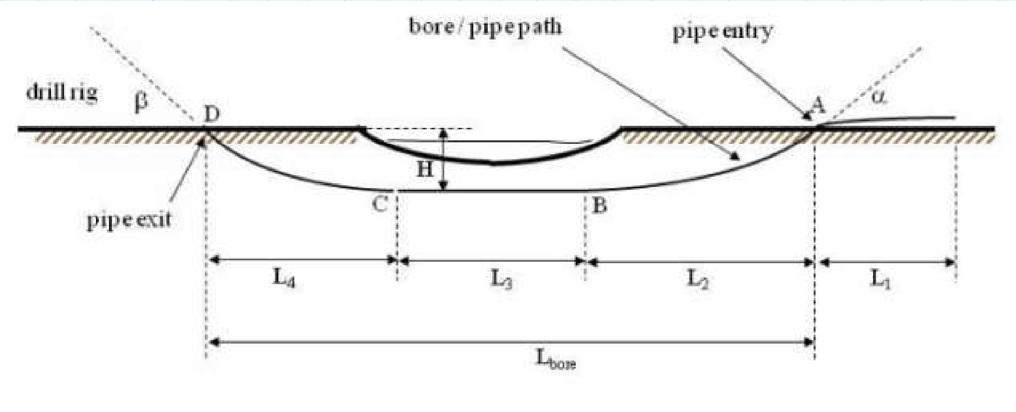


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 10\ °$ $\alpha_{in} := \alpha = 0.1745\ rad$	Borehole entry angle (degrees, radians)
$\beta := 12\ °$ $\beta_{exit} := \beta = 0.2094\ rad$	Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$	Final reamed bore diameter
$H_{max} := 41.6\ ft$	Max depth of bore hole to final reamed bore diameter
$H_{max1} := H_{max} + \frac{D_r}{2} = 42.35\ ft$	Max depth to bore hole springline from ground surface
$L_{total} := 2441\ ft$	Total length of HDD crossing
$L_1 := 150\ ft$	Assumed pipe drag on surface, See Illustration 1
$L_2 := 256.8\ ft$	Horizontal length to achieve depth - provided by Contractor, See Illustration 1
$L_{3\_1} := 1362.5\ ft$	Straight horizontal section, before curve
$L_{3\_2} := 332.6\ ft$	Curve Length
$L_{3\_3} := 193.1\ ft$	Straight horizontal section, after curve

$L_4 := 289.6\ ft$	Horizontal distance to rise to surface, See Illustration 1
$H := 39.9\ ft$	Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1
$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 67\ pcf = 9\ \frac{lbf}{gal}$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.1$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

$R_{avg.\_in} := 1000\ ft$	Radius of curvature at the entry, provided by Contractor
$R_{avg.\_out} := 1000\ ft$	Radius of curvature at the exit, provided by Contractor
$R := \frac{R_{avg.\_in} + R_{avg.\_out}}{2} = 1000\ ft$	Average radius of curvature at entry
$r_{rod} := 1200 \cdot D_{rod} = 350\ ft$	ASTM F 1962-99, Equation 1, p7

$Check := \text{if}\left(R_{avg.\_in} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

$Check := \text{if}\left(R_{avg.\_out} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

Radius of curvature should exceed 40 times the pipe outside diameter to prevent ring collapse.

$e_a := \frac{D_1}{2 \cdot R} = 0.0004$	Strain within the casing pipe
$E_{12hr} := 57500 \cdot psi$	Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)
$S_a := e_a \cdot E_{12hr} = 25.8\ psi$	Axial bending stress within the casing pipe

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

$$w_a := \frac{\pi}{4}\left(\left(D_1^{\,2} - \left(D_1 - T_{p1}\right)^2\right) + \left(D_2^{\,2} - \left(D_2 - T_{p2}\right)^2\right)\right) \cdot \rho_w \cdot \gamma_a = 8.3\ \boldsymbol{plf}$$

Effective weight

B1.2 - Upward Buoyant Force:

$$w_b := \left(\frac{\pi \cdot \left(D_1^{\,2} + D_2^{\,2}\right)}{4}\right) \rho_w \cdot \gamma_b - w_a = 36\ \boldsymbol{plf}$$

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

$$\Delta T := \Delta P \cdot \left(\frac{\pi}{8}\right)\left(D_r^{\,2} - \left(D_1^{\,2} + D_2^{\,2}\right)\right) = 796\ \boldsymbol{lbf}$$

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_{3\_1} + L_{3\_2} + L_{3\_3} + L_4\right)\right) = 2180\ \boldsymbol{lbf}$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}}\left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 6570\ \boldsymbol{lbf}$$

Pullback force increase with depth

B1.6 - Pullback Force Point C1:

$$T_{c\_1} := T_b + \left(v_b \cdot w_b \cdot L_{3\_1}\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 20076\ \boldsymbol{lbf}$$

B1.7 - Pullback Force Point C2:

$$\alpha_{curve} := 19.1\ °$$

$$T_{c\_2} := e^{v_b \cdot \alpha_{curve}}\left(T_{c\_1} + v_b \cdot \left|w_b\right| \cdot L_{3\_2} + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_{3\_2} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 27498\ \boldsymbol{lbf}$$

B1.8 - Pullback Force Point C3:

$$T_{c\_3} := T_{c\_2} + \left(v_b \cdot w_b \cdot L_{3\_3}\right) - e^{\left(v_b \cdot \alpha_{curve}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_3} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 29401\ \boldsymbol{lbf}$$

B1.9 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{c\_3} + v_b \cdot \left|w_b\right| \cdot L_4 - w_b \cdot H_{max} - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 32778\ \boldsymbol{lbf}$$

B1.10 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_{c\_1}, T_{c\_2}, T_{c\_3}, T_d\right) + \Delta T = 33575\ \boldsymbol{lbf}$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi \cdot D_1^{\ 2}\right)}{4}\right) \cdot \rho_w \cdot \left(\gamma_b - \gamma_c \cdot \left(1 - \left(\frac{2}{DR_1}\right)\right)^2\right) - w_a = 10.2\ plf$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_{3\_1} + L_{3\_2} + L_{3\_3} + L_4\right)\right) = 2180\ lbf$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 3794\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C1:

$$T_{c1\_filled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_1}\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 6732\ lbf$$

B2.5 - Pullback Force Point C2:

$\alpha_{curve} = 19.1\ °$

$$T_{c2\_filled} := e^{v_b \cdot \alpha_{curve}} \left(T_{c1\_filled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_2} + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_{3\_2} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 9341\ lbf$$

B2.6 - Pullback Force Point C3:

$$T_{c3\_filled} := T_{c2\_filled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_3}\right) - e^{\left(v_b \cdot \alpha_{curve}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 8639\ lbf$$

B2.7 - Pullback Force at D:

$$T_{dfilled} := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{c3\_filled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 9873\ lbf$$

B2.8 - Maximum Pullback Force - Filled Pipe with Water:

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{c1\_filled}, T_{c2\_filled}, T_{c3\_filled}, T_{dfilled}\right) = 9873\ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

$$A_1 := \frac{\pi}{4}\left(D_1^{\ 2} - \left(D_1 - T_{p1}\right)^2\right) = 19\ in^2$$ Cross-sectional area of Pipe 1

$$A_2 := \frac{\pi}{4}\left(D_2^{\ 2} - \left(D_2 - T_{p2}\right)^2\right) = 0.8\ in^2$$ Cross-sectional area of Pipe 2

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 32272\ lbf$$ Pullback forces acting on Pipe 1 (Empty)

$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 1303\ lbf$ Pullback forces acting on Pipe 2 (Empty)

$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 9490\ lbf$ Pullback forces acting on Pipe 1 (Ballast)

$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 383\ lbf$ Pullback forces acting on Pipe 2 (Ballast)

$P_{SPF1} := 41214\ lbf$ Safe pullback forces Pipe 1 (Table %, p. 448, PPI)

$P_{SPF2} := 1683\ lbf$ Safe pullback forces Pipe 2 (Table %, p. 448, PPI)

$check := \text{if}\left(P_{SPF1} > P_{11}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$
$check := \text{if}\left(P_{SPF2} > P_{21}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$
$check := \text{if}\left(P_{SPF1} > P_{12}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$
$check := \text{if}\left(P_{SPF2} > P_{22}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

-MathCAD calculations are used for a critical structure as identified for each crossing. If the HDD alignment crosses multiple structures the one with least cover was used. Provided hydrofracture graphs use equations, as detailed herein, to identify potential frac-out areas. Typically entry and exit areas are most susceptible to frac-out due to low cover.

-Where applicable, soil properties referenced from Kiewit's Proposed Soil Properties for CHPE Package 1, dated October 12, 2022.

$H_w := 17.7 \cdot ft$ — Depth of the bore below groundwater elevation

$H_c := 17.7\ ft$ — Vertical separation distance between critical structure and pipe (Coaxsackie Creek controls ~15+50)

$\gamma := 100\ pcf$ — Assumed unit weight soft to clay/silt (zero blow count material)

$\gamma_w := 62.4\ pcf$ — Unit weight of water

$\gamma' := \gamma - \gamma_w = 37.6\ pcf$ — Effective unit weight

$u := \gamma_w \cdot H_w = 8\ psi$ — Initial pore water pressure

$\phi := 0\ deg$ — Assumed friction Angle (B K-210.1 %-200=66%)

$c := 450\ psf = 3.13\ psi$ — Assumed cohesion of encountered materia (KIE suggests Su=300-350 psf)

$R_0 := \dfrac{D_{rod}}{2} = 1.75\ in$ — Initial radius of the borehole

$R_{pmax} := \dfrac{1}{2} \cdot H_c = 9\ ft$ — Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := \left(\left(\gamma \cdot \left(H_c - H_w\right)\right) + \gamma' \cdot H_w\right) = 5\ psi$ — Initial effective stress

Table C.2 Typical values of modulus of elasticity (E_S) for different types of soils

Type of Soil	E_s (N/mm²)
Clay	
Very soft	2–15
Soft	5–25
Medium	15–50
Hard	50–100
Sandy	25–250
Glacial till	
Loose	10–153
Dense	144–720
Very dense	478–1,440
Loess	14–57
Sand	
Silty	7–21
Loose	10–24
Dense	48–81
Sand and gravel	
Loose	48–148
Dense	96–192
Shale	144–14,400
Silt	2–20

$E_s := 5\ \dfrac{N}{mm^2} = 725\ psi$

Assumed modulus of elasticity

Table C.4 Typical values of Poisson's ratio (μ) for soils

Type of soil	μ
Clay (saturated)	0.4 – 0.5
Clay (unsaturated)	0.1 – 0.3
Sandy clay	0.2 – 0.3
Silt	0.3 – 0.35
Sand (dense)	0.2 – 0.4
Course (void ratio = 0.4 – 0.7)	0.15
Fine grained (void ratio = 0.4 – 0.7)	0.25
Rock	0.1–0.4 (depends on type of rock)
Loess	0.1 – 0.3
Ice	0.36
Concrete	0.15

$\nu_s := 0.4$

Poissions ratio of material encountered

$$G := \frac{E_s}{2\left(1+\nu_s\right)} = 259\ psi$$

Shear modulus of soil

$$Q := \frac{\left(\sigma'_0 \cdot \sin(\phi)\right) + (c \cdot 0)}{G} = 0$$

Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot (1 + \sin(\phi)) + c \cdot \cos(\phi) = 7.7\ psi$$

Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + (c \cdot 0)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot 0 = 7.7\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$$p_{max} := u + p'_{max} = 15.4\ psi$$

Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

$D_{PT} := 5\ in$ — Pilot tube diameter

$D_0 := 9.5\ in$ — Initial borehole diameter for pilot tube

$h := 38.9\ ft$ — Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 67\ pcf$ — Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 18.1\ psi$ — Minimum required mud pressure to overcome differntial head

$Q_f := 200\ gpm$ — Assumed mud flow rate

$$\tau_o := 16\ \frac{lbf}{100 \cdot ft^2}$$

Assumed yield point of mud per 100 square feet

$$\mu_{pl} := 25 \cdot \frac{poise}{100}$$

Assumed plastic viscosity of mud

$$v := \frac{Q_f}{0.785\left(D_0^{\,2} - D_{PT}^{\,2}\right)} = 75.2\ \frac{ft}{min}$$

Computed mud flow velocity

$L_{total} = 2441\ ft$

Total length of HDD crossing

$$p_2 := L_{total} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2}\right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)}\right)\right) = 7.3\ psi$$

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 25.4\ psi$

Minimum required mud pressure

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

D1.1 - Overburden Pressure (Considering Deformed Borehole with Arching Mobilized)

$H_c := H_{max} = 41.6\ ft$ Depth of cover

$\phi = 0\ deg$ Friction angle of soil

$B := D_r = 18\ in$ "Silo" width, conservative value = reamed hole diameter

$K := \tan\left(45 - \frac{\phi}{2}\right)^2$ Earth pressure coefficient

$\gamma = 100\ pcf$ Unit weight of soil, assumed

$k := \frac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)\right)}{\boxed{2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)}} = ?\ k := 1$ Arching factor (Eq. 6, p.432, PPI)

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 11\ psi \quad P_E = 1564\ psf$ Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

$E_{short} := 57500 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)

$k_{short} := \frac{E_{short}}{12 \cdot (DR_1 - 1)^3} = 9.36\ psi$ Variable in earth load deflection equation

$\Delta y_{ELD\_short} := \frac{0.0125 \cdot P_E}{k_{short}} = 1.5\%$ Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437, PPI Handbook)

D1.3 Earth Load Deflection (Long Term)

$E_{long} := 28200 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$k := \frac{E_{long}}{12 \cdot (DR_1 - 1)^3} = 4.6\ psi$ Variable in earth load deflection equation

$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 3.0\%$ Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437)

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

$D_1 = 10.75\ in$ — Outside diameter of casing pipe

$t := T_{p1} = 1.194\ in$ — Thickness of casing pipe

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit (Table B.1.1)

$\gamma_m = 67\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

$I := \frac{t^3}{12} = 0.14\ \frac{in^4}{in}$ — Moment of inertia of pipe wall cross section

$$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.0$$

Pipe ring deflection to buoyant force ASTM F 1962 (Eq. X2.6, p.6)

D2.1 Buoyant Deflection (Long Term)

Please note that long term buoyant deflection was assumed negibile, since grout is assumed to be cured after a 1-week period from installation/pumping.

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{short}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.0000033$$

Deflection due to longitudinal bending

$$\Delta y_{R\_short} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material at long term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{long}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.000003$$

Deflection due to longitudinal bending

$$\Delta y_{R\_long} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

$\Delta y_{lim} := 7.5\%$

Deflection limit for DR 9 non pressurized pipe (Table 2 , p. 437, PPI Handbook)

D4.1 - Net Short Term

$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 1.5\%$

Percent ring deflection in short term analysis

$Check := \text{if}\left(\Delta y_{short\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 3.0\%$

Percent ring deflection in long term analysis (50 years)

$Check := \text{if}\left(\Delta y_{long\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5 - Unconstrained Ring Buckling

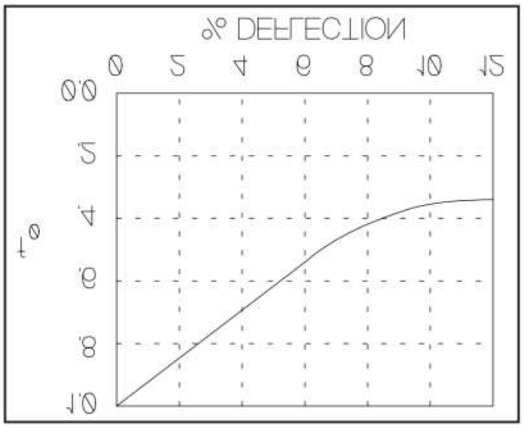
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ Factor of Safety

$\mu_{short} := 0.35$ Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$E_{short} = 57500\ psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)



Ovality compensation factor, Figure 3 (PPI Chp. 12). Calculated deflection limit in section D4.1

$f_{o\_short} := 0.88$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1 - \mu_{short}^{2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_short}}{N} = 112.6\ psi$$ Allowable unconstrained buckling pressure

$H = 39.9\ ft$ Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 18.56\ psi$ Pressure of drilling slurry

$P_{net} := P_{mud} = 18.56\ psi$ Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_short} > P_{net}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

D5.2 - Unconstrained Ring Buckling, Levy's Equation (Long Term)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ Factor of Safety

$\mu_{long} := 0.45$ Poisson's Ratio for PE pipe material, long term (ASTM F 1962, 8.2.4.2)

$E_{long} = 28200\ psi$

Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$f_{o\_long} := 0.45$

Ovality compensation factor, Figure 3 (PPI Chp. 12). Use deflection limit calculated in Section D4.2

$$P_{UC\_long} := \left(\frac{2 \cdot E_{long}}{1 - {\mu_{long}}^2}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_long}}{N} = 31.1\ psi$$

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 7.67\ psi$

Groundwater head pressure

$P_{net} := P_{GW}$

Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_long} > P_{net}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

References

1. ASTM F 1962 -05 Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings

2. ASTM F 1804-08 Standard Practice for Determining Allowable Tensile Load for Polyethylene (PE) Gas Pipe During Pull-In Installation

3. Proposed Soil Properties for CHPE Package 1 HDDs, Kiewit, October 12, 2022.

4. Handbook of Polyethylete Pipe, 2008, Plastics Pipe Institute (PPI), Second Edition

5. Larry Slavin, 2009, Guidelines for Use of Mini-Horizontal Direction Drilling for Placement of High Density Polyethylene Pipe

6. Mohammad Najafi, 2013, Trenchless Technology, First Edition, McGraw Hill

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Defining Parameters of Horizontal Directional Drilling :

$D_1 := 10.75\ in$ Pipe 1 outer diameter

$D_2 := 2.375\ in$ Pipe 2 outer diameter

$D_{rod} := 3.5\ in$ Assumed drill rod diameter

$DR_1 := 9$ Dimension ratio of Pipe 1

$DR_2 := 11$ Dimension ratio of Pipe 2

$T_{p1} := \frac{D_1}{DR_1} = 1.194\ in$ Thickness of Pipe 1

$T_{p2} := \frac{D_2}{DR_2} = 0.216\ in$ Thickness of Pipe 2

$C_1 := \pi \cdot D_1 = 33.8\ in$ Pipe circumference of pipe 1

$C_2 := \pi \cdot D_2 = 7.5\ in$ Pipe circumference of pipe 2

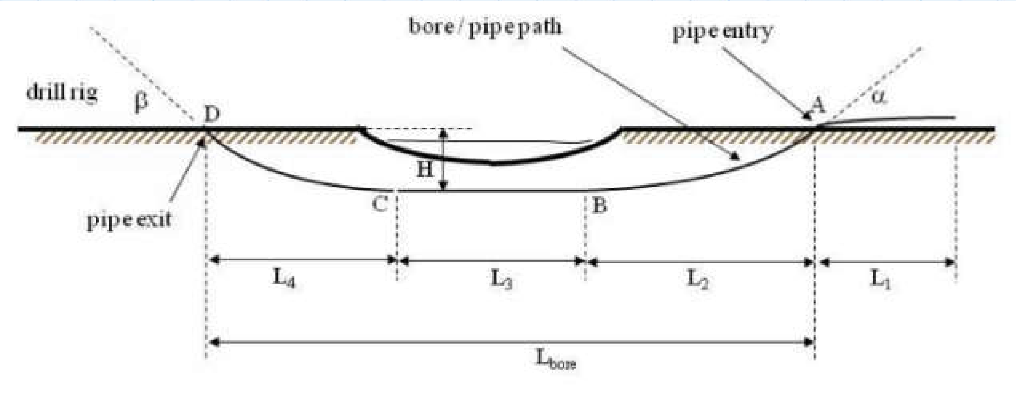


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 8\ °$ $\alpha_{in} := \alpha = 0.1396\ rad$ Borehole entry angle (degrees, radians)

$\beta := 10\ °$ $\beta_{exit} := \beta = 0.1745\ rad$ Borehole exit angle (degrees, radians)

$D_r := 18 \cdot in$ Final reamed bore diameter

$H_{max} := 36\ ft$ Max depth of bore hole to final reamed bore diameter

$H_{max1} := H_{max} + \frac{D_r}{2} = 36.75\ ft$ Max depth to bore hole springline from ground surface

$L_{total} := 1994.3\ ft$ Total length of HDD crossing

$L_1 := 150\ ft$ Assumed pipe drag on surface, See Illustration 1

$L_2 := 325.6\ ft$ Horizontal length to achieve depth - provided by Contractor, See Illustration 1

$L_{3\_1} := 1001\ ft$ Straight horizontal section, before curve

$L_{3\_2} := 104.6\ ft$ Curve Length

$L_{3\_3} := 65.3\ ft$ Straight horizontal section, after curve

$L_4 := 232.5\ ft$	Horizontal distance to rise to surface, See Illustration 1
$H := 25.5\ ft$	Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1
$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 67\ pcf = 9\ \frac{lbf}{gal}$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.1$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

$R_{avg.\_in} := 1000\ ft$	Radius of curvature at the entry, provided by Contractor
$R_{avg.\_out} := 1000\ ft$	Radius of curvature at the exit, provided by Contractor
$R := \frac{R_{avg.\_in} + R_{avg.\_out}}{2} = 1000\ ft$	Average radius of curvature at entry
$r_{rod} := 1200 \cdot D_{rod} = 350\ ft$	ASTM F 1962-99, Equation 1, p7

$Check := \text{if}\left(R_{avg.\_in} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

$Check := \text{if}\left(R_{avg.\_out} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

Radius of curvature should exceed 40 times the pipe outside diameter to prevent ring collapse.

$e_a := \frac{D_1}{2 \cdot R} = 0.0004$	Strain within the casing pipe
$E_{12hr} := 57500 \cdot psi$	Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)
$S_a := e_a \cdot E_{12hr} = 25.8\ psi$	Axial bending stress within the casing pipe

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

$$w_a := \frac{\pi}{4}\left(\left(D_1^{\,2} - \left(D_1 - T_{p1}\right)^2\right) + \left(D_2^{\,2} - \left(D_2 - T_{p2}\right)^2\right)\right) \cdot \rho_w \cdot \gamma_a = 8.3\ plf$$

B1.2 - Upward Buoyant Force:

Effective weight

$$w_b := \left(\frac{\pi \cdot \left(D_1^{\,2} + D_2^{\,2}\right)}{4}\right) \rho_w \cdot \gamma_b - w_a = 36\ plf$$

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

$$\Delta T := \Delta P \cdot \left(\frac{\pi}{8}\right)\left(D_r^{\,2} - \left(D_1^{\,2} + D_2^{\,2}\right)\right) = 796\ lbf$$

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_{3\_1} + L_{3\_2} + L_{3\_3} + L_4\right)\right) = 1579\ lbf$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}} \left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 6380\ lbf$$

Pullback force increase with depth

B1.6 - Pullback Force Point C1:

$$T_{c\_1} := T_b + \left(v_b \cdot w_b \cdot L_{3\_1}\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 16315\ lbf$$

B1.7 - Pullback Force Point C2:

$$\alpha_{curve} := 6.9\ °$$

$$T_{c\_2} := e^{v_b \cdot \alpha_{curve}} \left(T_{c\_1} + v_b \cdot \left|w_b\right| \cdot L_{3\_2} + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_{3\_2} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 19339\ lbf$$

B1.8 - Pullback Force Point C3:

$$T_{c\_3} := T_{c\_2} + \left(v_b \cdot w_b \cdot L_{3\_3}\right) - e^{\left(v_b \cdot \alpha_{curve}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_3} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 19988\ lbf$$

B1.9 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{c\_3} + v_b \cdot \left|w_b\right| \cdot L_4 - w_b \cdot H_{max} - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 22134\ lbf$$

B1.10 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_{c\_1}, T_{c\_2}, T_{c\_3}, T_d\right) + \Delta T = 22930\ lbf$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi \cdot D_1^{\ 2}\right)}{4}\right) \cdot \rho_w \cdot \left(\gamma_b - \gamma_c \cdot \left(1 - \left(\frac{2}{DR_1}\right)\right)^2\right) - w_a = 10.2\ plf$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_{3\_1} + L_{3\_2} + L_{3\_3} + L_4\right)\right) = 1579\ lbf$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 3347\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C1:

$$T_{c1\_filled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_1}\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 5518\ lbf$$

B2.5 - Pullback Force Point C2:

$\alpha_{curve} = 6.9\ °$

$$T_{c2\_filled} := e^{v_b \cdot \alpha_{curve}} \left(T_{c1\_filled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_2} + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_{3\_2} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 6521\ lbf$$

B2.6 - Pullback Force Point C3:

$$T_{c3\_filled} := T_{c2\_filled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_3}\right) - e^{\left(v_b \cdot \alpha_{curve}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 5849\ lbf$$

B2.7 - Pullback Force at D:

$$T_{dfilled} := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{c3\_filled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 6701\ lbf$$

B2.8 - Maximum Pullback Force - Filled Pipe with Water:

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{c1\_filled}, T_{c2\_filled}, T_{c3\_filled}, T_{dfilled}\right) = 6701\ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

$$A_1 := \frac{\pi}{4}\left(D_1^{\ 2} - \left(D_1 - T_{p1}\right)^2\right) = 19\ in^2$$

Cross-sectional area of Pipe 1

$$A_2 := \frac{\pi}{4}\left(D_2^{\ 2} - \left(D_2 - T_{p2}\right)^2\right) = 0.8\ in^2$$

Cross-sectional area of Pipe 2

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 22041\ lbf$$

Pullback forces acting on Pipe 1 (Empty)

$P_{21} := \dfrac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 890\ lbf$ Pullback forces acting on Pipe 2 (Empty)

$P_{12} := \dfrac{A_1 \cdot P_{max}}{A_1 + A_2} = 6441\ lbf$ Pullback forces acting on Pipe 1 (Ballast)

$P_{22} := \dfrac{A_2 \cdot P_{max}}{A_1 + A_2} = 260\ lbf$ Pullback forces acting on Pipe 2 (Ballast)

$P_{SPF1} := 41214\ lbf$ Safe pullback forces Pipe 1 (Table %, p. 448, PPI)

$P_{SPF2} := 1683\ lbf$ Safe pullback forces Pipe 2 (Table %, p. 448, PPI)

$check := \text{if}\left(P_{SPF1} > P_{11}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$
$check := \text{if}\left(P_{SPF2} > P_{21}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$
$check := \text{if}\left(P_{SPF1} > P_{12}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$
$check := \text{if}\left(P_{SPF2} > P_{22}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

-MathCAD calculations are used for a critical structure as identified for each crossing. If the HDD alignment crosses multiple structures the one with least cover was used. Provided hydrofracture graphs use equations, as detailed herein, to identify potential frac-out areas. Typically entry and exit areas are most susceptible to frac-out due to low cover.

-Where applicable, soil properties referenced from Kiewit's Proposed Soil Properties for CHPE Package 1, dated October 12, 2022.

$H_w := 15 \cdot ft$ — Depth of the bore below groundwater elevation

$H_c := 15\ ft$ — Vertical separation distance between critical structure and pipe (~11+50)

$\gamma := 100\ pcf$ — Assumed unit weight soft to clay/silt (zero blow count material)

$\gamma_w := 62.4\ pcf$ — Unit weight of water

$\gamma' := \gamma - \gamma_w = 37.6\ pcf$ — Effective unit weight

$u := \gamma_w \cdot H_w = 7\ psi$ — Initial pore water pressure

$\phi := 15\ deg$ — Assumed friction Angle

$c := 450\ psf = 3.13\ psi$ — Assumed cohesion of encountered material

$R_0 := \dfrac{D_{rod}}{2} = 1.75\ in$ — Initial radius of the borehole

$R_{pmax} := \dfrac{1}{2} \cdot H_c = 8\ ft$ — Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := (\gamma \cdot (H_c - H_w)) + \gamma' \cdot H_w = 4\ psi$ — Initial effective stress

Table C.2 Typical values of modulus of elasticity (E_S) for different types of soils

Type of Soil	E_s (N/mm^2)
Clay	
Very soft	2–15
Soft	5–25
Medium	15–50
Hard	50–100
Sandy	25–250
Glacial till	
Loose	10–153
Dense	144–720
Very dense	478–1,440
Loess	14–57
Sand	
Silty	7–21
Loose	10–24
Dense	48–81
Sand and gravel	
Loose	48–148
Dense	96–192
Shale	144–14,400
Silt	2–20

$E_s := 5\ \dfrac{N}{mm^2} = 725\ psi$

Assumed modulus of elasticity

Table C.4 Typical values of Poisson's ratio (μ) for soils

Type of soil	μ
Clay (saturated)	0.4 – 0.5
Clay (unsaturated)	0.1 – 0.3
Sandy clay	0.2 – 0.3
Silt	0.3 – 0.35
Sand (dense)	0.2 – 0.4
Course (void ratio = 0.4 – 0.7)	0.15
Fine grained (void ratio = 0.4 – 0.7)	0.25
Rock	0.1–0.4 (depends on type of rock)
Loess	0.1 – 0.3
Ice	0.36
Concrete	0.15

$\nu_s := 0.4$

Poissions ratio of material encountered

$$G := \frac{E_s}{2\left(1+\nu_s\right)} = 259\ psi$$

Shear modulus of soil

$$Q := \frac{\left(\sigma'_0 \cdot \sin(\phi)\right) + (c \cdot 0)}{G} = 0.0039$$

Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot (1+\sin(\phi)) + c \cdot \cos(\phi) = 7.9\ psi$$

Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + (c \cdot 0)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot 0 = 24.4\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$p_{max} := u + p'_{max} = 30.9\ psi$ Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

$D_{PT} := 5\ in$ Pilot tube diameter

$D_0 := 9.5\ in$ Initial borehole diameter for pilot tube

$h := 45\ ft$ Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 67\ pcf$ Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 20.9\ psi$ Minimum required mud pressure to overcome differntial head

$Q_f := 200\ gpm$ Assumed mud flow rate

$$\tau_o := 16\ \frac{lbf}{100 \cdot ft^2}$$

Assumed yield point of mud per 100 square feet

$$\mu_{pl} := 25 \cdot \frac{poise}{100}$$

Assumed plastic viscosity of mud

$$v := \frac{Q_f}{0.785\left(D_0^{\,2} - D_{PT}^{\,2}\right)} = 75.2\ \frac{ft}{min}$$

Computed mud flow velocity

$$L_{structure} := 1150\ ft$$

Length to structure

$$p_2 := L_{structure} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2}\right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)}\right)\right) = 3.4\ psi$$

Minimum required mud pressure to create flow inside the borehole

$$p_{min.} := p_1 + p_2 = 24.4\ psi$$

Minimum required mud pressure

$$check := \text{if}\left(p_{max} > p_{min.}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$$

Preventative measures should be taken to limit the potential of inadvertent returns.

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

D1.1 - Overburden Pressure (Considering Deformed Borehole with Arching Mobilized)

$H_c := H_{max} = 36\ ft$ — Depth of cover

$\phi = 15\ deg$ — Friction angle of soil

$B := D_r = 18\ in$ — "Silo" width, conservative value = reamed hole diameter

$K := \tan\left(45 - \frac{\phi}{2}\right)^2$ — Earth pressure coefficient

$\gamma = 100\ pcf$ — Unit weight of soil, assumed

$$k := \frac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)\right)}{2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)} = 0.105$$

$k := 1$

Arching factor (Eq. 6, p.432, PPI)

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 9\ psi$ $\quad P_E = 1354\ psf$ — Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

$E_{short} := 57500 \cdot psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)

$$k_{short} := \frac{E_{short}}{12 \cdot (DR_1 - 1)^3} = 9.36\ psi$$

Variable in earth load deflection equation

$$\Delta y_{ELD\_short} := \frac{0.0125 \cdot P_E}{k_{short}} = 1.3\%$$

Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437, PPI Handbook)

D1.3 Earth Load Deflection (Long Term)

$E_{long} := 28200 \cdot psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$$k := \frac{E_{long}}{12 \cdot (DR_1 - 1)^3} = 4.6\ psi$$

Variable in earth load deflection equation

$$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 2.6\%$$

Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437)

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

$D_1 = 10.75\ in$ — Outside diameter of casing pipe

$t := T_{p1} = 1.194\ in$ — Thickness of casing pipe

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit (Table B.1.1)

$\gamma_m = 67\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

$I := \frac{t^3}{12} = 0.14\ \frac{in^4}{in}$ — Moment of inertia of pipe wall cross section

$$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.0$$

Pipe ring deflection to buoyant force ASTM F 1962 (Eq. X2.6, p.6)

D2.1 Buoyant Deflection (Long Term)

Please note that long term buoyant deflection was assumed negibile, since grout is assumed to be cured after a 1-week period from installation/pumping.

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{short}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.0000033$$

Deflection due to longitudinal bending

$$\Delta y_{R\_short} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material at long term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{long}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.000003$$

Deflection due to longitudinal bending

$$\Delta y_{R\_long} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

$\Delta y_{lim} := 7.5\%$

Deflection limit for DR 9 non pressurized pipe (Table 2 , p. 437, PPI Handbook)

D4.1 - Net Short Term

$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 1.3\%$

Percent ring deflection in short term analysis

$Check := \text{if}\left(\Delta y_{short\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 2.6\%$

Percent ring deflection in long term analysis (50 years)

$Check := \text{if}\left(\Delta y_{long\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5 - Unconstrained Ring Buckling

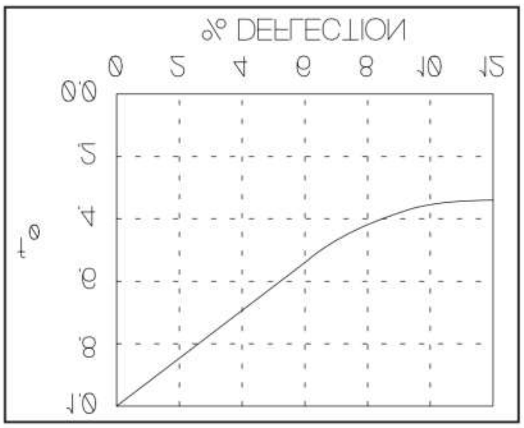
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ — Factor of Safety

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)



Ovality compensation factor, Figure 3 (PPI Chp. 12). Calculated deflection limit in section D4.1

$f_{o\_short} := 0.88$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1 - \mu_{short}^{\ 2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_short}}{N} = 112.6\ psi$$

Allowable unconstrained buckling pressure

$H = 25.5\ ft$ — Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 11.86\ psi$ — Pressure of drilling slurry

$P_{net} := P_{mud} = 11.86\ psi$ — Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_short} > P_{net}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5.2 - Unconstrained Ring Buckling, Levy's Equation (Long Term)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ — Factor of Safety

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material, long term (ASTM F 1962, 8.2.4.2)

$E_{long} = 28200\ psi$

Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$f_{o\_long} := 0.45$

Ovality compensation factor, Figure 3 (PPI Chp. 12). Use deflection limit calculated in Section D4.2

$$P_{UC\_long} := \left(\frac{2 \cdot E_{long}}{1 - {\mu_{long}}^2}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_long}}{N} = 31.1\ psi$$

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 6.5\ psi$

Groundwater head pressure

$P_{net} := P_{GW}$

Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_long} > P_{net}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

References

1. ASTM F 1962 -05 Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings

2. ASTM F 1804-08 Standard Practice for Determining Allowable Tensile Load for Polyethylene (PE) Gas Pipe During Pull-In Installation

3. Proposed Soil Properties for CHPE Package 1 HDDs, Kiewit, October 12, 2022.

4. Handbook of Polyethylete Pipe, 2008, Plastics Pipe Institute (PPI), Second Edition

5. Larry Slavin, 2009, Guidelines for Use of Mini-Horizontal Direction Drilling for Placement of High Density Polyethylene Pipe

6. Mohammad Najafi, 2013, Trenchless Technology, First Edition, McGraw Hill

Defining Parameters of Horizontal Directional Drilling :

$D_1 := 10.75\ in$ Pipe 1 outer diameter
$D_2 := 2.375\ in$ Pipe 2 outer diameter
$D_{rod} := 3.5\ in$ Assumed drill rod diameter
$DR_1 := 9$ Dimension ratio of Pipe 1
$DR_2 := 11$ Dimension ratio of Pipe 2

$T_{p1} := \frac{D_1}{DR_1} = 1.194\ in$ Thickness of Pipe 1
$T_{p2} := \frac{D_2}{DR_2} = 0.216\ in$ Thickness of Pipe 2

$C_1 := \pi \cdot D_1 = 33.8\ in$ Pipe circumference of pipe 1
$C_2 := \pi \cdot D_2 = 7.5\ in$ Pipe circumference of pipe 2

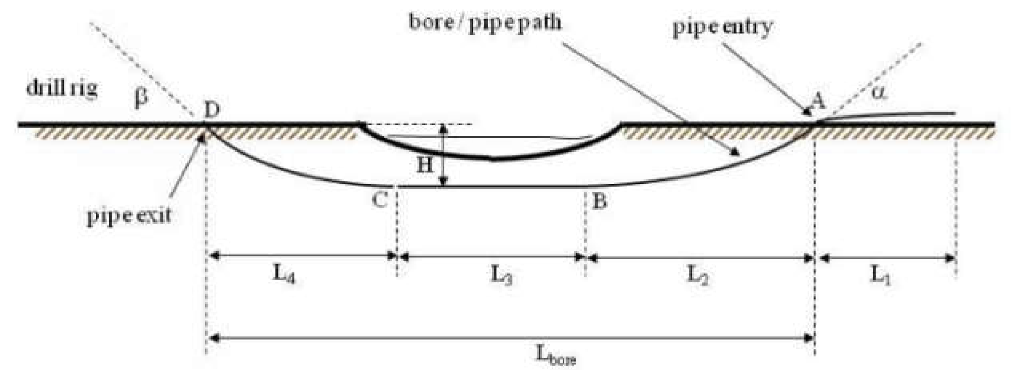


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 10\ °$ $\alpha_{in} := \alpha = 0.1745\ rad$ Borehole entry angle (degrees, radians)
$\beta := 10\ °$ $\beta_{exit} := \beta = 0.1745\ rad$ Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$ Final reamed bore diameter
$H_{max} := 21.40\ ft$ Max depth of bore hole to final reamed bore diameter

$H_{max1} := H_{max} + \frac{D_r}{2} = 22.15\ ft$ Max depth to bore hole springline from ground surface

$L_{total} := 531.7\ ft$ Total length of HDD crossing

$L_1 := 150\ ft$ Assumed pipe drag on surface, See Illustration 1

$L_2 := 211.7\ ft$ Horizontal length to achieve depth - provided by Contractor, See Illustration 1

$L_3 := 104.3\ ft$ Straight horizontal section
$L_4 := 215.7\ ft$ Horizontal distance to rise to surface, See Illustration 1

$H := 21.66\ ft$ Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1

$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 70\ pcf = 9.4\ \frac{lbf}{gal}$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.1$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

$R_{avg.\_in} := 1000\ ft$	Radius of curvature at the entry, provided by Contractor
$R_{avg.\_out} := 1000\ ft$	Radius of curvature at the exit, provided by Contractor
$R := \frac{R_{avg.\_in} + R_{avg.\_out}}{2} = 1000\ ft$	Average radius of curvature at entry
$r_{rod} := 1200 \cdot D_{rod} = 350\ ft$	ASTM F 1962-99, Equation 1, p7

$Check := \text{if}\left(R_{avg.\_in} > r_{rod}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

$Check := \text{if}\left(R_{avg.\_out} > r_{rod}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

Radius of curvature should exceed 40 times the pipe outside diameter to prevent ring collapse.

$e_a := \frac{D_1}{2 \cdot R} = 0.0004$	Strain within the casing pipe
$E_{12hr} := 57500 \cdot psi$	Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)
$S_a := e_a \cdot E_{12hr} = 25.8\ psi$	Axial bending stress within the casing pipe

B - Site Specific Analyses: Pullback Force (C1 controls):

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

$$w_a := \frac{\pi}{4}\left(\left(D_1^{\,2}-\left(D_1-T_{p1}\right)^2\right)+\left(D_2^{\,2}-\left(D_2-T_{p2}\right)^2\right)\right)\cdot\rho_w\cdot\gamma_a = 8.3\ plf$$

B1.2 - Upward Buoyant Force: Effective weight

$$w_b := \left(\frac{\pi\cdot\left(D_1^{\,2}+D_2^{\,2}\right)}{4}\right)\rho_w\cdot\gamma_b - w_a = 38\ plf$$ Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

$$\Delta T := \Delta P\cdot\left(\frac{\pi}{8}\right)\left(D_r^{\,2}-\left(D_1^{\,2}+D_2^{\,2}\right)\right) = 796\ lbf$$ Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a\cdot\alpha_{in}}\cdot\left(v_a\cdot w_a\cdot\left(L_1+L_2+L_3+L_4\right)\right) = 575\ lbf$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b\cdot\alpha_{in}}\left(T_a+v_b\cdot\left|w_b\right|\cdot L_2+w_b\cdot H_{max}-v_a\cdot w_a\cdot L_2\cdot e^{\left(v_a\cdot\alpha_{in}\right)}\right) = 3817\ lbf$$

Pullback force increase with depth

B1.6 - Pullback Force Point C:

$$T_c := T_b+\left(v_b\cdot w_b\cdot L_3\right)-e^{\left(v_b\cdot\alpha_{in}\right)}\cdot\left(v_a\cdot w_a\cdot L_3\cdot e^{\left(v_a\cdot\alpha_{in}\right)}\right) = 4912\ lbf$$

B1.7 - Pullback Force at D:

$$T_d := e^{\left(v_b\cdot\beta_{exit}\right)}\cdot\left(T_c+v_b\cdot\left|w_b\right|\cdot L_4-w_b\cdot H_{max}-e^{\left(v_a\cdot\alpha_{in}\right)}\cdot\left(v_a\cdot w_a\cdot L_4\cdot e^{\left(v_a\cdot\alpha_{in}\right)}\right)\right) = 6715\ lbf$$

B1.8 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_c, T_d\right)+\Delta T = 7512\ lbf$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi\cdot D_1^{\,2}\right)}{4}\right)\cdot\rho_w\cdot\left(\gamma_b-\gamma_c\cdot\left(1-\left(\frac{2}{DR_1}\right)\right)^2\right)-w_a = 12\ plf$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a\cdot\alpha_{in}}\cdot\left(v_a\cdot w_a\cdot\left(L_1+L_2+L_3+L_4\right)\right) = 575\ lbf$$ Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 1871 \; lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C:

$$T_{cfilled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_3\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 2155 \; lbf$$

B2.5 - Pullback Force at D:

$$T_{dfilled} := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{cfilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 2897 \; lbf$$

B2.6 - Maximum Pullback Force - Filled Pipe with Water:

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{cfilled}, T_{dfilled}\right) = 2897 \; lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

$$A_1 := \frac{\pi}{4}\left(D_1^{\,2} - \left(D_1 - T_{p1}\right)^2\right) = 19 \; in^2$$ Cross-sectional area of Pipe 1

$$A_2 := \frac{\pi}{4}\left(D_2^{\,2} - \left(D_2 - T_{p2}\right)^2\right) = 0.8 \; in^2$$ Cross-sectional area of Pipe 2

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 7220 \; lbf$$ Pullback forces acting on Pipe 1 (Empty)

$$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 291 \; lbf$$ Pullback forces acting on Pipe 2 (Empty)

$$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 2785 \; lbf$$ Pullback forces acting on Pipe 1 (Ballast)

$$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 112 \; lbf$$ Pullback forces acting on Pipe 2 (Ballast)

$$P_{SPF1} := 41214 \; lbf$$ Safe pullback forces Pipe 1 (Table %, p. 448, PPI)

$$P_{SPF2} := 1683 \; lbf$$ Safe pullback forces Pipe 2 (Table %, p. 448, PPI)

$$check := \text{if}\left(P_{SPF1} > P_{11}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$
$$check := \text{if}\left(P_{SPF2} > P_{21}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$
$$check := \text{if}\left(P_{SPF1} > P_{12}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$
$$check := \text{if}\left(P_{SPF2} > P_{22}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

-MathCAD calculations are used for a critical structure as identified for each crossing. If the HDD alignment crosses multiple structures the one with least cover was used. Provided hydrofracture graphs use equations, as detailed herein, to identify potential frac-out areas. Typically entry and exit areas are most susceptible to frac-out due to low cover.

-Where applicable, soil properties referenced from Kiewit's Proposed Soil Properties for CHPE Package 1, dated October 12, 2022.

$H_w := 10.2 \cdot ft$ Depth of the bore below groundwater elevation

$H_c := 21.29\ ft$ Vertical separation distance between critical structure and pipe (CSX, MP 211.8)

$\gamma := 100\ pcf$ Assumed unit weight soft to clay/silt (zero blow count material)

$\gamma_w := 62.4\ pcf$ Unit weight of water

$\gamma' := \gamma - \gamma_w = 37.6\ pcf$ Effective unit weight

$u := \gamma_w \cdot H_w = 4\ psi$ Initial pore water pressure

$\phi := 0\ deg$ Assumed friction Angle

$c := 450\ psf = 3.13\ psi$ Assumed cohesion of encountered materia (KIE suggests Su=300-350 psf)

$R_0 := \frac{D_{rod}}{2} = 1.75\ in$ Initial radius of the borehole

$R_{pmax} := \frac{1}{2} \cdot H_c = 11\ ft$ Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := \left(\left(\gamma \cdot \left(H_c - H_w\right)\right) + \gamma' \cdot H_w\right) = 10\ psi$ Initial effective stress

Table C.2 Typical values of modulus of elasticity (E_S) for different types of soils

Type of Soil	E_s (N/mm^2)
Clay	
Very soft	2–15
Soft	5–25
Medium	15–50
Hard	50–100
Sandy	25–250
Glacial till	
Loose	10–153
Dense	144–720
Very dense	478–1,440
Loess	14–57
Sand	
Silty	7–21
Loose	10–24
Dense	48–81
Sand and gravel	
Loose	48–148
Dense	96–192
Shale	144–14,400
Silt	2–20

$E_s := 2\ \frac{N}{mm^2} = 290\ psi$

Assumed modulus of elasticity

Table C.4 Typical values of Poisson's ratio (μ) for soils

Type of soil	μ
Clay (saturated)	0.4 – 0.5
Clay (unsaturated)	0.1 – 0.3
Sandy clay	0.2 – 0.3
Silt	0.3 – 0.35
Sand (dense)	0.2 – 0.4
Course (void ratio = 0.4 – 0.7)	0.15
Fine grained (void ratio = 0.4 – 0.7)	0.25
Rock	0.1–0.4 (depends on type of rock)
Loess	0.1 – 0.3
Ice	0.36
Concrete	0.15

$\nu_s := 0.4$ Poissions ratio of material encountered

$$G := \frac{E_s}{2\left(1+\nu_s\right)} = 104\ psi$$ Shear modulus of soil

$$Q := \frac{\left(\sigma'_0 \cdot \sin(\phi)\right)+(c \cdot 0)}{G} = 0$$ Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot (1+\sin(\phi)) + c \cdot \cos(\phi) = 13.5\ psi$$ Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + (c \cdot 0)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot 0 = 13.5\ psi$$ Maximum allowable effective mud pressure (Delft Equation)

$$p_{max} := u + p'_{max} = 17.9\ psi$$ Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

$D_{PT} := 5\ in$ Pilot tube diameter

$D_0 := 9.5\ in$ Initial borehole diameter for pilot tube

$h := 21.4\ ft$ Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 70\ pcf$ Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 10.4\ psi$ Minimum required mud pressure to overcome differntial head

$Q_f := 200\ gpm$ Assumed mud flow rate

$$\tau_o := 16\ \frac{lbf}{100 \cdot ft^2}$$ Assumed yield point of mud per 100 square feet

$$\mu_{pl} := 25 \cdot \frac{poise}{100}$$ Assumed plastic viscosity of mud

$$v := \frac{Q_f}{0.785\left(D_0^{\ 2} - D_{PT}^{\ 2}\right)} = 75.2\ \frac{ft}{min}$$ Computed mud flow velocity

$L_{structure} := 225\ ft$ Length to sturcture

$$p_2 := L_{structure} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2} \right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)} \right) \right) = 0.7\ psi$$

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 11.1\ psi$ Minimum required mud pressure

$check := \text{if}\left(p_{max} > p_{min.}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

D1.1 - Overburden Pressure (Considering Deformed Borehole with Arching Mobilized)

$H_c := H_{max} = 21.4\ ft$	Depth of cover
$\phi = 0\ deg$	Friction angle of soil
$B := D_r = 18\ in$	"Silo" width, conservative value = reamed hole diameter
$K := \tan\left(45 - \frac{\phi}{2}\right)^2$	Earth pressure coefficient
$\gamma = 100\ pcf$	Unit weight of soil, assumed
$k := \frac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)\right)}{\boxed{2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)}} = ?\ k := 1$	Arching factor (Eq. 6, p.432, PPI)
$P_L := 300\ psf$	Live loading for E80 (RR at 20-feet depth)
$P_E := (k \cdot (\gamma - \gamma_w) \cdot (H_c)) + P_L = 8\ psi$	Effective overburden pressure
$P_E = 1105\ psf$	

D1.2 Earth Load Deflection (Short Term)

$E_{short} := 57500 \cdot psi$	Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)
$k_{short} := \frac{E_{short}}{12 \cdot (DR_1 - 1)^3} = 9.36\ psi$	Variable in earth load deflection equation
$\Delta y_{ELD\_short} := \frac{0.0125 \cdot P_E}{k_{short}} = 1.0\%$	Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437, PPI Handbook)

D1.3 Earth Load Deflection (Long Term)

$E_{long} := 28200 \cdot psi$	Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)
$k := \frac{E_{long}}{12 \cdot (DR_1 - 1)^3} = 4.6\ psi$	Variable in earth load deflection equation
$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 2.1\%$	Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437)

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

$D_1 = 10.75\ in$ — Outside diameter of casing pipe

$t := T_{p1} = 1.194\ in$ — Thickness of casing pipe

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit (Table B.1.1)

$\gamma_m = 70\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

$I := \frac{t^3}{12} = 0.14\ \frac{in^4}{in}$ — Moment of inertia of pipe wall cross section

$$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.0$$

Pipe ring deflection to buoyant force ASTM F 1962 (Eq. X2.6, p.6)

D2.1 Buoyant Deflection (Long Term)

Please note that long term buoyant deflection was assumed negibile, since grout is assumed to be cured after a 1-week period from installation/pumping.

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{short}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.0000033$$

Deflection due to longitudinal bending

$$\Delta y_{R\_short} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material at long term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{long}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.000003$$

Deflection due to longitudinal bending

$$\Delta y_{R\_long} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

$$\Delta y_{lim} := 7.5\%$$

Deflection limit for DR 9 non pressurized pipe (Table 2 , p. 437, PPI Handbook)

D4.1 - Net Short Term

$$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 1.1\%$$

Percent ring deflection in short term analysis

$$Check := \text{if}\left(\Delta y_{short\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$$

D4.2 - Net Long Term

$$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 2.1\%$$

Percent ring deflection in long term analysis (50 years)

$$Check := \text{if}\left(\Delta y_{long\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$$

D5 - Unconstrained Ring Buckling

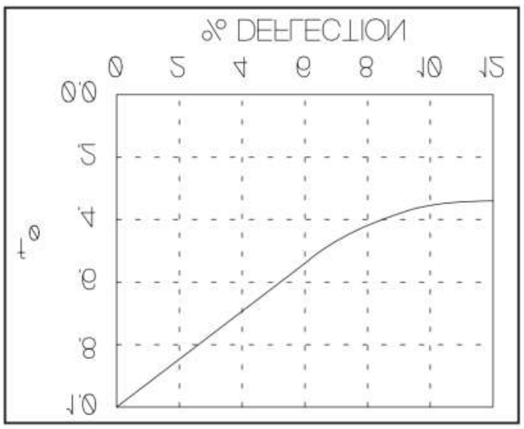
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ Factor of Safety

$\mu_{short} := 0.35$ Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$E_{short} = 57500\ psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)



Ovality compensation factor, Figure 3 (PPI Chp. 12). Calculated deflection limit in section D4.1

$f_{o\_short} := 0.88$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1-\mu_{short}^{\ 2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_short}}{N} = 112.6\ psi$$

Allowable unconstrained buckling pressure

$H = 21.66\ ft$ Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 10.53\ psi$ Pressure of drilling slurry

$P_{net} := P_{mud} = 10.53\ psi$ Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_short} > P_{net}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

D5.2 - Unconstrained Ring Buckling, Levy's Equation (Long Term)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ Factor of Safety

$\mu_{long} := 0.45$ Poisson's Ratio for PE pipe material, long term (ASTM F 1962, 8.2.4.2)

$E_{long} = 28200\ psi$

Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$f_{o\_long} := 0.45$

Ovality compensation factor, Figure 3 (PPI Chp. 12). Use deflection limit calculated in Section D4.2

$$P_{UC\_long} := \left(\frac{2 \cdot E_{long}}{1 - {\mu_{long}}^2}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_long}}{N} = 31.1\ psi$$

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 4.42\ psi$

Groundwater head pressure

$P_{net} := P_{GW}$

Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_long} > P_{net}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

References

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107.A

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$D_1 := 10.75\ in$	Pipe 1 outer diameter
$D_2 := 2.375\ in$	Pipe 2 outer diameter
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$DR_1 := 9$	Dimension ratio of Pipe 1
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$T_{p1} := \frac{D_1}{DR_1} = 1.194\ in$	Thickness of Pipe 1
$T_{p2} := \frac{D_2}{DR_2} = 0.216\ in$	Thickness of Pipe 2
$C_1 := \pi \cdot D_1 = 33.8\ in$	Pipe circumference of pipe 1
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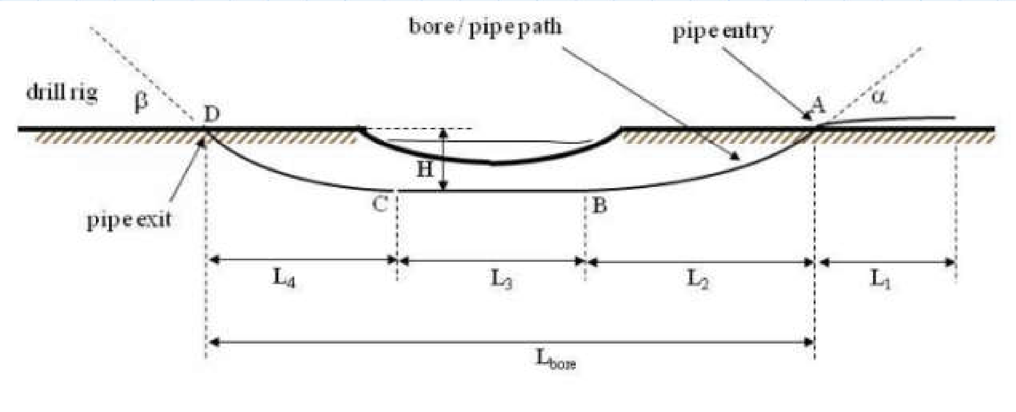


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 10\ °$ $\quad \alpha_{in} := \alpha = 0.1745\ rad$	Borehole entry angle (degrees, radians)
$\beta := 10\ °$ $\quad \beta_{exit} := \beta = 0.1745\ rad$	Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$	Final reamed bore diameter
$H_{max} := 30\ ft$	Max depth of bore hole to final reamed bore diameter
$H_{max1} := H_{max} + \frac{D_r}{2} = 30.75\ ft$	Max depth to bore hole springline from ground surface
$L_{total} := 819\ ft$	Total length of HDD crossing
$L_1 := 150\ ft$	Assumed pipe drag on surface, See Illustration 1
$L_2 := 269\ ft$	Horizontal length to achieve depth - provided by Contractor, See Illustration 1
$L_3 := 314\ ft$	Straight horizontal section
$L_4 := 236\ ft$	Horizontal distance to rise to surface, See Illustration 1
$H := 29\ ft$	Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1

$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 67\ pcf$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.1$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

$R_{avg.\_in} := 1000\ ft$	Radius of curvature at the entry, provided by Contractor
$R_{avg.\_out} := 1000\ ft$	Radius of curvature at the exit, provided by Contractor
$R := \frac{R_{avg.\_in} + R_{avg.\_out}}{2} = 1000\ ft$	Average radius of curvature at entry
$r_{rod} := 1200 \cdot D_{rod} = 350\ ft$	ASTM F 1962-99, Equation 1, p7

$Check := \text{if}\left(R_{avg.\_in} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

$Check := \text{if}\left(R_{avg.\_out} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

Radius of curvature should exceed 40 times the pipe outside diameter to prevent ring collapse.

$e_a := \frac{D_1}{2 \cdot R} = 0.0004$	Strain within the casing pipe
$E_{12hr} := 57500 \cdot psi$	Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)
$S_a := e_a \cdot E_{12hr} = 25.8\ psi$	Axial bending stress within the casing pipe

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

$$w_a := \frac{\pi}{4}\left(\left(D_1^2 - \left(D_1 - T_{p1}\right)^2\right) + \left(D_2^2 - \left(D_2 - T_{p2}\right)^2\right)\right) \cdot \rho_w \cdot \gamma_a = 8.3\ plf$$

B1.2 - Upward Buoyant Force: Effective weight

$$w_b := \left(\frac{\pi \cdot \left(D_1^2 + D_2^2\right)}{4}\right) \rho_w \cdot \gamma_b - w_a = 36\ plf$$ Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

$$\Delta T := \Delta P \cdot \left(\frac{\pi}{8}\right)\left(D_r^2 - \left(D_1^2 + D_2^2\right)\right) = 796\ lbf$$ Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 817\ lbf$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}}\left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 4822\ lbf$$

Pullback force increase with depth

B1.6 - Pullback Force Point C:

$$T_c := T_b + \left(v_b \cdot w_b \cdot L_3\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 7934\ lbf$$

B1.7 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_c + v_b \cdot \left|w_b\right| \cdot L_4 - w_b \cdot H_{max} - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 9695\ lbf$$

B1.8 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_c, T_d\right) + \Delta T = 10492\ lbf$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi \cdot D_1^2\right)}{4}\right) \cdot \rho_w \cdot \left(\gamma_b - \gamma_c \cdot \left(1 - \left(\frac{2}{DR_1}\right)\right)^2\right) - w_a = 10.2\ plf$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 817\ lbf$$ Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 2284\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C:

$$T_{cfilled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_3\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 2961\ lbf$$

B2.5 - Pullback Force at D:

$$T_{dfilled} := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{cfilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 3664\ lbf$$

B2.6 - Maximum Pullback Force - Filled Pipe with Water:

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{cfilled}, T_{dfilled}\right) = 3664\ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

$A_1 := \frac{\pi}{4}\left(D_1^2 - \left(D_1 - T_{p1}\right)^2\right) = 19\ in^2$ Cross-sectional area of Pipe 1

$A_2 := \frac{\pi}{4}\left(D_2^2 - \left(D_2 - T_{p2}\right)^2\right) = 0.8\ in^2$ Cross-sectional area of Pipe 2

$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 10085\ lbf$ Pullback forces acting on Pipe 1 (Empty)

$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 407\ lbf$ Pullback forces acting on Pipe 2 (Empty)

$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 3522\ lbf$ Pullback forces acting on Pipe 1 (Ballast)

$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 142\ lbf$ Pullback forces acting on Pipe 2 (Ballast)

$P_{SPF1} := 41214\ lbf$ Safe pullback forces Pipe 1 (Table %, p. 448, PPI)

$P_{SPF2} := 1683\ lbf$ Safe pullback forces Pipe 2 (Table %, p. 448, PPI)

$check := \text{if}\left(P_{SPF1} > P_{11}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$
$check := \text{if}\left(P_{SPF2} > P_{21}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$
$check := \text{if}\left(P_{SPF1} > P_{12}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$
$check := \text{if}\left(P_{SPF2} > P_{22}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

-MathCAD calculations are used for a critical structure as identified for each crossing. If the HDD alignment crosses multiple structures the one with least cover was used. Provided hydrofracture graphs use equations, as detailed herein, to identify potential frac-out areas. Typically entry and exit areas are most susceptible to frac-out due to low cover.

-Where applicable, soil properties referenced from Kiewit's Proposed Soil Properties for CHPE Package 1, dated October 12, 2022.

$H_w := 0 \cdot ft$ Depth of the bore below groundwater elevation

$H_c := 30\ ft$ Vertical separation distance between critical structure and pipe (CSX Tracks)

$\gamma := 140\ pcf$ Assumed unit weight of bedrock(no geotech available)

$\gamma_w := 62.4\ pcf$ Unit weight of water

$\gamma' := \gamma - \gamma_w = 77.6\ pcf$ Effective unit weight

$u := \gamma_w \cdot H_w = 0\ psi$ Initial pore water pressure

$\phi := 35\ deg$ Assumed friction Angle (no geotech available)

$c := 450\ psf = 3.13\ psi$ Assumed cohesion of encountered material

$R_0 := \dfrac{D_{rod}}{2} = 1.75\ in$ Initial radius of the borehole

$R_{pmax} := \dfrac{1}{2} \cdot H_c = 15\ ft$ Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := \left(\left(\gamma \cdot \left(H_c - H_w\right)\right) + \gamma' \cdot H_w\right) = 29\ psi$ Initial effective stress

Table C.2 Typical values of modulus of elasticity (E_s) for different types of soils

Type of Soil	E_s (N/mm^2)
Clay	
Very soft	2–15
Soft	5–25
Medium	15–50
Hard	50–100
Sandy	25–250
Glacial till	
Loose	10–153
Dense	144–720
Very dense	478–1,440
Loess	14–57
Sand	
Silty	7–21
Loose	10–24
Dense	48–81
Sand and gravel	
Loose	48–148
Dense	96–192
Shale	144–14,400
Silt	2–20

$E_s := 28\ \dfrac{N}{mm^2} = 4061\ psi$

Assumed modulus of elasticity

Table C.4 Typical values of Poisson's ratio (μ) for soils

Type of soil	μ
Clay (saturated)	0.4 – 0.5
Clay (unsaturated)	0.1 – 0.3
Sandy clay	0.2 – 0.3
Silt	0.3 – 0.35
Sand (dense)	0.2 – 0.4
Course (void ratio = 0.4 – 0.7)	0.15
Fine grained (void ratio = 0.4 – 0.7)	0.25
Rock	0.1–0.4 (depends on type of rock)
Loess	0.1 – 0.3
Ice	0.36
Concrete	0.15

$\nu_s := 0.4$

Poissions ratio of material encountered

$G := \dfrac{E_s}{2\,(1+\nu_s)} = 1450\ psi$ Shear modulus of soil

$Q := \dfrac{(\sigma'_0 \cdot \sin(\phi)) + (c \cdot 0)}{G} = 0.0115$

Coefficient of Delft Equation

$p'_f := \sigma'_0 \cdot (1 + \sin(\phi)) + c \cdot \cos(\phi) = 48.5\ psi$

Mud pressure at which the first plastic deformation takes place

$$p'_{max} := (p'_f + (c \cdot 0)) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}} \right)^2 + Q \right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)} \right)} \right) - c \cdot 0 = 245.7\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$p_{max} := u + p'_{max} = 245.7\ psi$ Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

$D_{PT} := 5\ in$ Pilot tube diameter

$D_0 := 9.5\ in$ Initial borehole diameter for pilot tube

$h := 29\ ft$ Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 67\ pcf$ Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 13.5\ psi$ Minimum required mud pressure to overcome differntial head

$Q_f := 200\ gpm$ Assumed mud flow rate

$\tau_o := 16\ \dfrac{lbf}{100 \cdot ft^2}$ Assumed yield point of mud per 100 square feet

$\mu_{pl} := 25 \cdot \dfrac{poise}{100}$ Assumed plastic viscosity of mud

$v := \dfrac{Q_f}{0.785\,({D_0}^2 - {D_{PT}}^2)} = 75.2\ \dfrac{ft}{min}$ Computed mud flow velocity

$L_{structure} := 300\ ft$ Length to sturcture

$$p_2 := L_{structure} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2} \right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)} \right) \right) = 0.9\ psi$$

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 14.4\ psi$ Minimum required mud pressure

$check := \text{if}\left(p_{max} > p_{min.}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

D1.1 - Overburden Pressure (Considering Deformed Borehole with Arching Mobilized)

$H_c := H_{max} = 30\ ft$ Depth of cover

$\phi = 35\ deg$ Friction angle of soil

$B := D_r = 18\ in$ "Silo" width, conservative value = reamed hole diameter

$K := \tan\left(45 - \frac{\phi}{2}\right)^2$ Earth pressure coefficient

$\gamma = 140\ pcf$ Unit weight of soil, assumed

$$k := \frac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)\right)}{2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)} = 0.106$$

Arching factor (Eq. 6, p.432, PPI)

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 2\ psi \quad P_E = 248\ psf$ Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

$E_{short} := 57500 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)

$$k_{short} := \frac{E_{short}}{12 \cdot (DR_1 - 1)^3} = 9.36\ psi$$

Variable in earth load deflection equation

$$\Delta y_{ELD\_short} := \frac{0.0125 \cdot P_E}{k_{short}} = 0.2\%$$

Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437, PPI Handbook)

D1.3 Earth Load Deflection (Long Term)

$E_{long} := 28200 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$$k := \frac{E_{long}}{12 \cdot (DR_1 - 1)^3} = 4.6\ psi$$

Variable in earth load deflection equation

$$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 0.5\%$$

Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437)

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

$D_1 = 10.75\ in$ — Outside diameter of casing pipe

$t := T_{p1} = 1.194\ in$ — Thickness of casing pipe

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit (Table B.1.1)

$\gamma_m = 67\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

$I := \frac{t^3}{12} = 0.14\ \frac{in^4}{in}$ — Moment of inertia of pipe wall cross section

$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.0$ — Pipe ring deflection to buoyant force ASTM F 1962 (Eq. X2.6, p.6)

D2.1 Buoyant Deflection (Long Term)

Please note that long term buoyant deflection was assumed negibile, since grout is assumed to be cured after a 1-week period from installation/pumping.

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{short}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.0000033$ — Deflection due to longitudinal bending

$\Delta y_{R\_short} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$ — Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material at long term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{long}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.000003$ — Deflection due to longitudinal bending

$\Delta y_{R\_long} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$ — Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

$\Delta y_{lim} := 7.5\%$

Deflection limit for DR 9 non pressurized pipe (Table 2 , p. 437, PPI Handbook)

D4.1 - Net Short Term

$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 0.3\%$

Percent ring deflection in short term analysis

$Check := \text{if}\left(\Delta y_{short\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 0.5\%$

Percent ring deflection in long term analysis (50 years)

$Check := \text{if}\left(\Delta y_{long\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5 - Unconstrained Ring Buckling

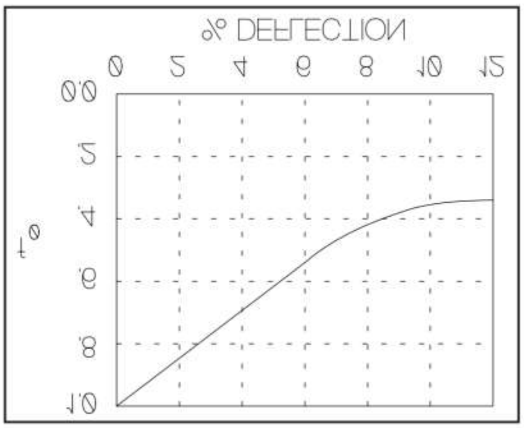
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ — Factor of Safety

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$E_{short} = 57500 \; psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)



Ovality compensation factor, Figure 3 (PPI Chp. 12). Calculated deflection limit in section D4.1

$f_{o\_short} := 0.9$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1 - \mu_{short}^{2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^{3} \cdot \frac{f_{o\_short}}{N} = 115.2 \; psi$$ Allowable unconstrained buckling pressure

$H = 29 \; ft$ — Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 13.49 \; psi$ — Pressure of drilling slurry

$P_{net} := P_{mud} = 13.49 \; psi$ — Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_short} > P_{net}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

D5.2 - Unconstrained Ring Buckling, Levy's Equation (Long Term)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ — Factor of Safety

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material, long term (ASTM F 1962, 8.2.4.2)

$E_{long} = 28200\ psi$

Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$f_{o\_long} := 0.45$

Ovality compensation factor, Figure 3 (PPI Chp. 12). Use deflection limit calculated in Section D4.2

$$P_{UC\_long} := \left(\frac{2 \cdot E_{long}}{1 - {\mu_{long}}^2}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_long}}{N} = 31.1\ psi$$

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 0\ psi$

Groundwater head pressure

$P_{net} := P_{GW}$

Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_long} > P_{net}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

References

1. ASTM F 1962 -05 Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings

2. ASTM F 1804-08 Standard Practice for Determining Allowable Tensile Load for Polyethylene (PE) Gas Pipe During Pull-In Installation

3. Proposed Soil Properties for CHPE Package 1 HDDs, Kiewit, October 12, 2022.

4. Handbook of Polyethylete Pipe, 2008, Plastics Pipe Institute (PPI), Second Edition

5. Larry Slavin, 2009, Guidelines for Use of Mini-Horizontal Direction Drilling for Placement of High Density Polyethylene Pipe

6. Mohammad Najafi, 2013, Trenchless Technology, First Edition, McGraw Hill

Defining Parameters of Horizontal Directional Drilling :

$D_1 := 10.75\ in$	Pipe 1 outer diameter
$D_2 := 2.375\ in$	Pipe 2 outer diameter
$D_{rod} := 3.5\ in$	Assumed drill rod diameter
$DR_1 := 9$	Dimension ratio of Pipe 1
$DR_2 := 11$	Dimension ratio of Pipe 2
$T_{p1} := \dfrac{D_1}{DR_1} = 1.194\ in$	Thickness of Pipe 1
$T_{p2} := \dfrac{D_2}{DR_2} = 0.216\ in$	Thickness of Pipe 2
$C_1 := \pi \cdot D_1 = 33.8\ in$	Pipe circumference of pipe 1
$C_2 := \pi \cdot D_2 = 7.5\ in$	Pipe circumference of pipe 2

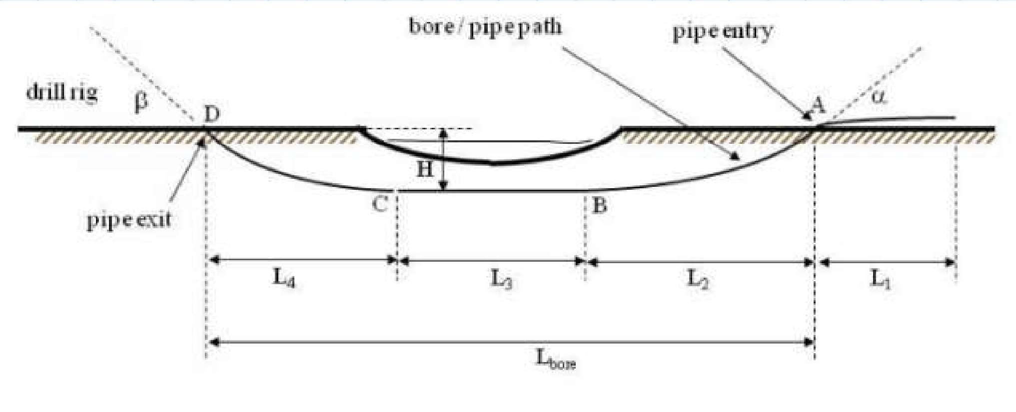


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 12\ °$ $\quad \alpha_{in} := \alpha = 0.2094\ rad$	Borehole entry angle (degrees, radians)
$\beta := 8\ °$ $\quad \beta_{exit} := \beta = 0.1396\ rad$	Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$	Final reamed bore diameter
$H_{max} := 45\ ft$	Max depth of bore hole to final reamed bore diameter
$H_{max1} := H_{max} + \dfrac{D_r}{2} = 45.75\ ft$	Max depth to bore hole springline from ground surface
$L_{total} := 2553.5\ ft$	Total length of HDD crossing
$L_1 := 150\ ft$	Assumed pipe drag on surface, See Illustration 1
$L_2 := 285.7\ ft$	Horizontal length to achieve depth - provided by Contractor, See Illustration 1
$L_{3\_1} := 48\ ft$	Straight horizontal section, before curve
$L_{3\_2} := 273.4\ ft$	Curve Length
$L_{3\_3} := 1066.5\ ft$	Straight horizontal section, after curve

$L_4 := 286.9 \cdot ft$	Horizontal distance to rise to surface, See Illustration 1
$H := 38.71\ ft$	Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1
$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 70\ pcf$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.1$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

$R_{avg.\_in} := 1000\ ft$	Radius of curvature at the entry, provided by Contractor
$R_{avg.\_out} := 1000\ ft$	Radius of curvature at the exit, provided by Contractor
$R := \frac{R_{avg.\_in} + R_{avg.\_out}}{2} = 1000\ ft$	Average radius of curvature at entry
$r_{rod} := 1200 \cdot D_{rod} = 350\ ft$	ASTM F 1962-99, Equation 1, p7

$Check := \text{if}\left(R_{avg.\_in} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

$Check := \text{if}\left(R_{avg.\_out} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

Radius of curvature should exceed 40 times the pipe outside diameter to prevent ring collapse.

$e_a := \frac{D_1}{2 \cdot R} = 0.0004$	Strain within the casing pipe
$E_{12hr} := 57500 \cdot psi$	Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)
$S_a := e_a \cdot E_{12hr} = 25.8\ psi$	Axial bending stress within the casing pipe

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

$$w_a := \frac{\pi}{4}\left(\left(D_1^{\,2} - \left(D_1 - T_{p1}\right)^2\right) + \left(D_2^{\,2} - \left(D_2 - T_{p2}\right)^2\right)\right) \cdot \rho_w \cdot \gamma_a = 8.3\ plf$$

Effective weight

B1.2 - Upward Buoyant Force:

$$w_b := \left(\frac{\pi \cdot \left(D_1^{\,2} + D_2^{\,2}\right)}{4}\right) \rho_w \cdot \gamma_b - w_a = 38\ plf$$

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

$$\Delta T := \Delta P \cdot \left(\frac{\pi}{8}\right) \left(D_r^{\,2} - \left(D_1^{\,2} + D_2^{\,2}\right)\right) = 796\ lbf$$

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_{3\_1} + L_{3\_2} + L_{3\_3} + L_4\right)\right) = 1786\ lbf$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}} \left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 6932\ lbf$$

Pullback force increase with depth

B1.6 - Pullback Force Point C1:

$$T_{c\_1} := T_b + \left(v_b \cdot w_b \cdot L_{3\_1}\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 7435\ lbf$$

B1.7 - Pullback Force Point C2:

$$\alpha_{curve} := 15.4\ °$$

$$T_{c\_2} := e^{v_b \cdot \alpha_{curve}} \left(T_{c\_1} + v_b \cdot \left|w_b\right| \cdot L_{3\_2} + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_{3\_2} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 13038\ lbf$$

B1.8 - Pullback Force Point C3:

$$T_{c\_3} := T_{c\_2} + \left(v_b \cdot w_b \cdot L_{3\_3}\right) - e^{\left(v_b \cdot \alpha_{curve}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_3} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 24208\ lbf$$

B1.9 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{c\_3} + v_b \cdot \left|w_b\right| \cdot L_4 - w_b \cdot H_{max} - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 26612\ lbf$$

B1.10 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_{c\_1}, T_{c\_2}, T_{c\_3}, T_d\right) + \Delta T = 27408\ lbf$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi \cdot D_1^{\,2}\right)}{4}\right) \cdot \rho_w \cdot \left(\gamma_b - \gamma_c \cdot \left(1 - \left(\frac{2}{DR_1}\right)\right)^2\right) - w_a = 12\ plf$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_{3\_1} + L_{3\_2} + L_{3\_3} + L_4\right)\right) = 1786\ lbf$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 3835\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C1:

$$T_{c1\_filled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_1}\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 3965\ lbf$$

B2.5 - Pullback Force Point C2:

$\alpha_{curve} = 15.4\ °$

$$T_{c2\_filled} := e^{v_b \cdot \alpha_{curve}} \left(T_{c1\_filled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_2} + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_{3\_2} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 6209\ lbf$$

B2.6 - Pullback Force Point C3:

$$T_{c3\_filled} := T_{c2\_filled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_3}\right) - e^{\left(v_b \cdot \alpha_{curve}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 10017\ lbf$$

B2.7 - Pullback Force at D:

$$T_{dfilled} := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{c3\_filled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 11267\ lbf$$

B2.8 - Maximum Pullback Force - Filled Pipe with Water:

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{c1\_filled}, T_{c2\_filled}, T_{c3\_filled}, T_{dfilled}\right) = 11267\ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

$$A_1 := \frac{\pi}{4}\left(D_1^{\,2} - \left(D_1 - T_{p1}\right)^2\right) = 19\ in^2$$

Cross-sectional area of Pipe 1

$$A_2 := \frac{\pi}{4}\left(D_2^{\,2} - \left(D_2 - T_{p2}\right)^2\right) = 0.8\ in^2$$

Cross-sectional area of Pipe 2

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 26345\ lbf$$

Pullback forces acting on Pipe 1 (Empty)

$P_{21} := \dfrac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 1063\ lbf$ Pullback forces acting on Pipe 2 (Empty)

$P_{12} := \dfrac{A_1 \cdot P_{max}}{A_1 + A_2} = 10830\ lbf$ Pullback forces acting on Pipe 1 (Ballast)

$P_{22} := \dfrac{A_2 \cdot P_{max}}{A_1 + A_2} = 437\ lbf$ Pullback forces acting on Pipe 2 (Ballast)

$P_{SPF1} := 41214\ lbf$ Safe pullback forces Pipe 1 (Table %, p. 448, PPI)

$P_{SPF2} := 1683\ lbf$ Safe pullback forces Pipe 2 (Table %, p. 448, PPI)

$check := \text{if}\left(P_{SPF1} > P_{11}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$
$check := \text{if}\left(P_{SPF2} > P_{21}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$
$check := \text{if}\left(P_{SPF1} > P_{12}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$
$check := \text{if}\left(P_{SPF2} > P_{22}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

-MathCAD calculations are used for a critical structure as identified for each crossing. If the HDD alignment crosses multiple structures the one with least cover was used. Provided hydrofracture graphs use equations, as detailed herein, to identify potential frac-out areas. Typically entry and exit areas are most susceptible to frac-out due to low cover.

-Where applicable, soil properties referenced from Kiewit's Proposed Soil Properties for CHPE Package 1, dated October 12, 2022.

$H_w := 25.8 \cdot ft$ — Depth of the bore below groundwater elevation

$H_c := 25.8\ ft$ — Vertical separation distance between critical structure and pipe (~3+00)

$\gamma := 100\ pcf$ — Assumed unit weight soft to clay/silt (zero blow count material)

$\gamma_w := 62.4\ pcf$ — Unit weight of water

$\gamma' := \gamma - \gamma_w = 37.6\ pcf$ — Effective unit weight

$u := \gamma_w \cdot H_w = 11\ psi$ — Initial pore water pressure

$\phi := 0\ deg$ — Assumed friction Angle

$c := 450\ psf = 3.13\ psi$ — Assumed cohesion of encountered material

$R_0 := \dfrac{D_{rod}}{2} = 1.75\ in$ — Initial radius of the borehole

$R_{pmax} := \dfrac{1}{2} \cdot H_c = 13\ ft$ — Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := \left(\gamma \cdot \left(H_c - H_w\right)\right) + \gamma' \cdot H_w = 7\ psi$ — Initial effective stress

Table C.2 Typical values of modulus of elasticity (E_S) for different types of soils

Type of Soil	E_s (N/mm^2)
Clay	
Very soft	2–15
Soft	5–25
Medium	15–50
Hard	50–100
Sandy	25–250
Glacial till	
Loose	10–153
Dense	144–720
Very dense	478–1,440
Loess	14–57
Sand	
Silty	7–21
Loose	10–24
Dense	48–81
Sand and gravel	
Loose	48–148
Dense	96–192
Shale	144–14,400
Silt	2–20

$E_s := 5\ \dfrac{N}{mm^2} = 725\ psi$

Assumed modulus of elasticity

Table C.4 Typical values of Poisson's ratio (μ) for soils

Type of soil	μ
Clay (saturated)	0.4 – 0.5
Clay (unsaturated)	0.1 – 0.3
Sandy clay	0.2 – 0.3
Silt	0.3 – 0.35
Sand (dense)	0.2 – 0.4
Course (void ratio = 0.4 – 0.7)	0.15
Fine grained (void ratio = 0.4 – 0.7)	0.25
Rock	0.1–0.4 (depends on type of rock)
Loess	0.1 – 0.3
Ice	0.36
Concrete	0.15

$\nu_s := 0.4$

Poissions ratio of material encountered

$$G := \frac{E_s}{2\left(1+\nu_s\right)} = 259\ psi$$

Shear modulus of soil

$$Q := \frac{\left(\sigma'_0 \cdot \sin(\phi)\right) + (c \cdot 0)}{G} = 0$$

Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot (1+\sin(\phi)) + c \cdot \cos(\phi) = 9.9\ psi$$

Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + (c \cdot 0)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot 0 = 9.9\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$p_{max} := u + p'_{max} = 21\ psi$ Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

$D_{PT} := 5\ in$ Pilot tube diameter

$D_0 := 9.5\ in$ Initial borehole diameter for pilot tube

$h := 38.6\ ft$ Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 70\ pcf$ Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 18.8\ psi$ Minimum required mud pressure to overcome differntial head

$Q_f := 200\ gpm$ Assumed mud flow rate

$\tau_o := 16\ \frac{lbf}{100 \cdot ft^2}$ Assumed yield point of mud per 100 square feet

$\mu_{pl} := 25 \cdot \frac{poise}{100}$ Assumed plastic viscosity of mud

$$v := \frac{Q_f}{0.785\left(D_0^{\ 2} - D_{PT}^{\ 2}\right)} = 75.2\ \frac{ft}{min}$$

Computed mud flow velocity

$L_{structure} := 385\ ft$ Length to sturcture

$$p_2 := L_{structure} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2} \right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)} \right) \right) = 1.2\ psi$$

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 19.9\ psi$ Minimum required mud pressure

$check := \text{if}\left(p_{max} > p_{min.}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

D1.1 - Overburden Pressure (Considering Deformed Borehole with Arching Mobilized)

$H_c := H_{max} = 45\ ft$ Depth of cover

$\phi = 0\ deg$ Friction angle of soil

$B := D_r = 18\ in$ "Silo" width, conservative value = reamed hole diameter

$K := \tan\left(45 - \frac{\phi}{2}\right)^2$ Earth pressure coefficient

$\gamma = 100\ pcf$ Unit weight of soil, assumed

$k := \dfrac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)\right)}{\boxed{2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)}} = ?\ k := 1$ Arching factor (Eq. 6, p.432, PPI)

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 12\ psi$ $P_E = 1692\ psf$ Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

$E_{short} := 57500 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)

$k_{short} := \dfrac{E_{short}}{12 \cdot (DR_1 - 1)^3} = 9.36\ psi$ Variable in earth load deflection equation

$\Delta y_{ELD\_short} := \dfrac{0.0125 \cdot P_E}{k_{short}} = 1.6\%$ Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437, PPI Handbook)

D1.3 Earth Load Deflection (Long Term)

$E_{long} := 28200 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$k := \dfrac{E_{long}}{12 \cdot (DR_1 - 1)^3} = 4.6\ psi$ Variable in earth load deflection equation

$\Delta y_{ELD\_long} := \dfrac{0.0125 \cdot P_E}{k} = 3.2\%$ Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437)

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

$D_1 = 10.75\ in$ — Outside diameter of casing pipe

$t := T_{p1} = 1.194\ in$ — Thickness of casing pipe

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit (Table B.1.1)

$\gamma_m = 70\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

$I := \frac{t^3}{12} = 0.14\ \frac{in^4}{in}$ — Moment of inertia of pipe wall cross section

$$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.0$$

Pipe ring deflection to buoyant force ASTM F 1962 (Eq. X2.6, p.6)

D2.1 Buoyant Deflection (Long Term)

Please note that long term buoyant deflection was assumed negibile, since grout is assumed to be cured after a 1-week period from installation/pumping.

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{short}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.0000033$$

Deflection due to longitudinal bending

$$\Delta y_{R\_short} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material at long term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{long}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.000003$$

Deflection due to longitudinal bending

$$\Delta y_{R\_long} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

$\Delta y_{lim} := 7.5\%$

Deflection limit for DR 9 non pressurized pipe (Table 2 , p. 437, PPI Handbook)

D4.1 - Net Short Term

$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 1.6\%$

Percent ring deflection in short term analysis

$Check := \text{if}\left(\Delta y_{short\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 3.2\%$

Percent ring deflection in long term analysis (50 years)

$Check := \text{if}\left(\Delta y_{long\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5 - Unconstrained Ring Buckling

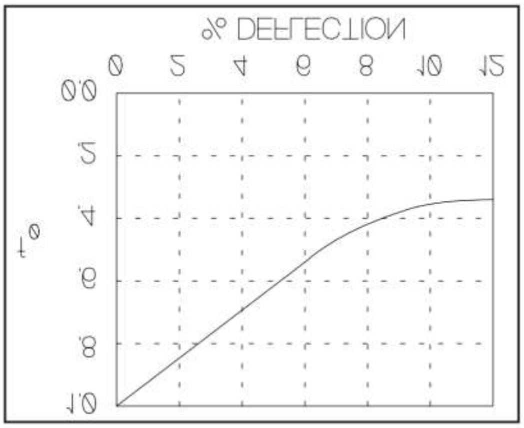
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ — Factor of Safety

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)



Ovality compensation factor, Figure 3 (PPI Chp. 12). Calculated deflection limit in section D4.1

$f_{o\_short} := 0.88$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1 - \mu_{short}^{\ 2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_short}}{N} = 112.6\ psi$$

Allowable unconstrained buckling pressure

$H = 38.71\ ft$ — Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 18.82\ psi$ — Pressure of drilling slurry

$P_{net} := P_{mud} = 18.82\ psi$ — Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_short} > P_{net}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5.2 - Unconstrained Ring Buckling, Levy's Equation (Long Term)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ — Factor of Safety

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material, long term (ASTM F 1962, 8.2.4.2)

$E_{long} = 28200\ psi$

Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$f_{o\_long} := 0.45$

Ovality compensation factor, Figure 3 (PPI Chp. 12). Use deflection limit calculated in Section D4.2

$$P_{UC\_long} := \left(\frac{2 \cdot E_{long}}{1 - {\mu_{long}}^2}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_long}}{N} = 31.1\ psi$$

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 11.18\ psi$

Groundwater head pressure

$P_{net} := P_{GW}$

Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_long} > P_{net}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

References

1. ASTM F 1962 -05 Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings

2. ASTM F 1804-08 Standard Practice for Determining Allowable Tensile Load for Polyethylene (PE) Gas Pipe During Pull-In Installation

3. Proposed Soil Properties for CHPE Package 1 HDDs, Kiewit, October 12, 2022.

4. Handbook of Polyethylete Pipe, 2008, Plastics Pipe Institute (PPI), Second Edition

5. Larry Slavin, 2009, Guidelines for Use of Mini-Horizontal Direction Drilling for Placement of High Density Polyethylene Pipe

6. Mohammad Najafi, 2013, Trenchless Technology, First Edition, McGraw Hill

Defining Parameters of Horizontal Directional Drilling :

$D_1 := 10.75\ in$ — Pipe 1 outer diameter

$D_2 := 3.5\ in$ — Pipe 2 outer diameter

$DR_1 := 9$ — Dimension ratio of Pipe 1

$DR_2 := 11$ — Dimension ratio of Pipe 2

$T_{p1} := \dfrac{D_1}{DR_1} = 1.194\ in$ — Thickness of Pipe 1

$T_{p2} := \dfrac{D_2}{DR_2} = 0.318\ in$ — Thickness of Pipe 2

$C_1 := \pi \cdot D_1 = 33.8\ in$ — Pipe circumference of pipe 1

$C_2 := \pi \cdot D_2 = 11\ in$ — Pipe circumference of pipe 2

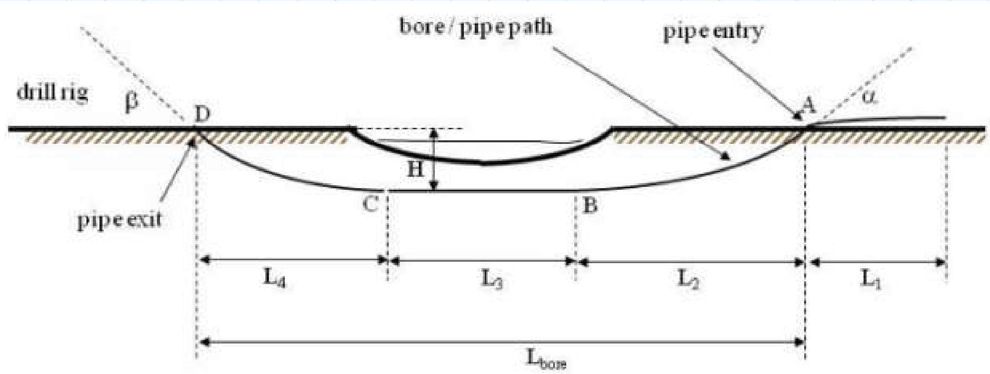


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 10\ °$ $\quad \alpha_{in} := \alpha = 0.1745\ rad$ — Borehole entry angle (degrees, radians)

$\beta := 8\ °$ $\quad \beta_{exit} := \beta = 0.1396\ rad$ — Borehole exit angle (degrees, radians)

$D_r := 18 \cdot in$ — Final reamed bore diameter

$H_{max} := 23.8\ ft$ — Max depth of bore hole from ground surface

$H_{max1} := H_{max} + \dfrac{D_r}{2} = 24.55\ ft$ — Max depth to bore hole springline from ground surface

$L_{total} := 556.5\ ft$ — Total length of HDD crossing

$L_1 := 150\ ft$ — Assumed pipe drag on surface, See Illustration 1

$L_2 := 49.8\ ft$ — Horizontal length to achieve depth - provided by Contractor, See Illustration 1

$L_3 := 73.2\ ft$ — Straight horizontal section

$L_4 := 233.9\ ft$ — Horizontal distance to rise to surface, See Illustration 1

$H := 25.2\ ft$ — Elevation difference between the lowest point in borehole and entry or exit pit, See Illustration 1

$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 70\ pcf$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.1$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

$R_{avg.\_in} := 1000\ ft$	Radius of curvature at the entry, provided by Contractor
$R_{avg.\_out} := 1000\ ft$	Radius of curvature at the exit, provided by Contractor
$R := \frac{R_{avg.\_in} + R_{avg.\_out}}{2} = 1000\ ft$	Average radius of curvature at entry
$r := 40 \cdot D_1 = 36\ ft$	

$Check := \text{if}\left(R_{avg.\_in} > r, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

$Check := \text{if}\left(R_{avg.\_out} > r, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

Radius of curvature should exceed 40 times the pipe outside diameter to prevent ring collapse.

$e_a := \frac{D_1}{2 \cdot R} = 0.0004$	Strain within the casing pipe
$E_{12hr} := 57500 \cdot psi$	Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)
$S_a := e_a \cdot E_{12hr} = 25.8\ psi$	Axial bending stress within the casing pipe

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

$$w_a := \frac{\pi}{4}\left(\left(D_1^{\ 2} - \left(D_1 - T_{p1}\right)^2\right) + \left(D_2^{\ 2} - \left(D_2 - T_{p2}\right)^2\right)\right) \cdot \rho_w \cdot \gamma_a = 8.7\ \mathit{plf}$$

Effective weight

B1.2 - Upward Buoyant Force:

$$w_b := \left(\frac{\pi \cdot \left(D_1^{\ 2} + D_2^{\ 2}\right)}{4}\right) \rho_w \cdot \gamma_b - w_a = 40.1\ \mathit{plf}$$

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

$$\Delta T := \Delta P \cdot \left(\frac{\pi}{8}\right)\left(D_r^{\ 2} - \left(D_1^{\ 2} + D_2^{\ 2}\right)\right) = 770\ \mathit{lbf}$$

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 447\ \mathit{lbf}$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}}\left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 2063\ \mathit{lbf}$$

Pullback force increase with depth

B1.6 - Pullback Force Point C:

$$T_c := T_b + \left(v_b \cdot w_b \cdot L_3\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 2876\ \mathit{lbf}$$

B1.7 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_c + v_b \cdot \left|w_b\right| \cdot L_4 - w_b \cdot H_{max} - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 4721\ \mathit{lbf}$$

B1.8 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_c, T_d\right) + \Delta T = 5492\ \mathit{lbf}$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi \cdot D_1^{\ 2}\right)}{4}\right) \cdot \rho_w \cdot \left(\gamma_b - \gamma_c \cdot \left(1 - \left(\frac{2}{DR_1}\right)\right)^2\right) - w_a = 11.7\ \mathit{plf}$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 447\ \mathit{lbf}$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 993\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C:

$$T_{cfilled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_3\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 1182\ lbf$$

B2.5 - Pullback Force at D:

$$T_{dfilled} := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{cfilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 1867\ lbf$$

B2.6 - Maximum Pullback Force - Filled Pipe with Water:

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{cfilled}, T_{dfilled}\right) = 1867\ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

$$A_1 := \frac{\pi}{4}\left(D_1^{\ 2} - \left(D_1 - T_{p1}\right)^2\right) = 19\ in^2$$ Cross-sectional area of Pipe 1

$$A_2 := \frac{\pi}{4}\left(D_2^{\ 2} - \left(D_2 - T_{p2}\right)^2\right) = 1.7\ in^2$$ Cross-sectional area of Pipe 2

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 5049\ lbf$$ Pullback forces acting on Pipe 1 (Empty)

$$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 443\ lbf$$ Pullback forces acting on Pipe 2 (Empty)

$$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 1716\ lbf$$ Pullback forces acting on Pipe 1 (Ballast)

$$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 150\ lbf$$ Pullback forces acting on Pipe 2 (Ballast)

$$P_{SPF1} := 41214\ lbf$$ Safe pullback forces Pipe 1 (Table %, p. 448, PPI)

$$P_{SPF2} := 1683\ lbf$$ Safe pullback forces Pipe 2 (Table %, p. 448, PPI)

$$check := \text{if}\left(P_{SPF1} > P_{11}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$
$$check := \text{if}\left(P_{SPF2} > P_{21}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$
$$check := \text{if}\left(P_{SPF1} > P_{12}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$
$$check := \text{if}\left(P_{SPF2} > P_{22}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

$H_w := 0 \cdot ft$ Depth of the bore below groundwater elevation

$H_c := 22.5\ ft$ Vertical separation distance between critical structure and pipe (~2+75)

$\gamma := 100\ pcf$ Unit weight of CH (K-216.2 and B-216.1)

$\gamma_w := 62.4\ pcf$ Unit weight of water

$\gamma' := \gamma - \gamma_w = 37.6\ pcf$ Effective unit weight

$u := \gamma_w \cdot H_w = 0\ psi$ Initial pore water pressure

$\phi := 0\ deg$ Friction Angle

$c := 450\ psf$ Assumed cohesion of encountered material

$R_0 := \frac{D_r}{2} = 9\ in$ Initial radius of the borehole

$R_{pmax} := \frac{1}{2} \cdot H_c = 11\ ft$ Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := (\gamma \cdot (H_c - H_w)) + \gamma' \cdot H_w = 16\ psi$ Initial effective stress (no GWT

Table C.2 Typical values of modulus of elasticity (E_S) for different types of soils

Type of Soil	E_s (N/mm^2)
Clay	
Very soft	2–15
Soft	5–25
Medium	15–50
Hard	50–100
Sandy	25–250
Glacial till	
Loose	10–153
Dense	144–720
Very dense	478–1,440
Loess	14–57
Sand	
Silty	7–21
Loose	10–24
Dense	48–81
Sand and gravel	
Loose	48–148
Dense	96–192
Shale	144–14,400
Silt	2–20

$E_s := 5\ \frac{N}{mm^2} = 725\ psi$

Assumed modulus of elasticity of CH

Table C.4 Typical values of Poisson's ratio (μ) for soils

Type of soil	μ
Clay (saturated)	0.4 – 0.5
Clay (unsaturated)	0.1 – 0.3
Sandy clay	0.2 – 0.3
Silt	0.3 – 0.35
Sand (dense)	0.2 – 0.4
Course (void ratio = 0.4 – 0.7)	0.15
Fine grained (void ratio = 0.4 – 0.7)	0.25
Rock	0.1–0.4 (depends on type of rock)
Loess	0.1 – 0.3
Ice	0.36
Concrete	0.15

$\nu_s := 0.4$

Poissions ratio of material encountered

$$G := \frac{E_s}{2\left(1+\nu_s\right)} = 258.996\ psi$$ Shear modulus of soil

$$Q := \frac{\left(\sigma'_0 \cdot \sin(\phi)\right) + (c \cdot 0)}{G} = 0$$ Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot (1 + \sin(\phi)) + c \cdot \cos(\phi) = 18.8\ psi$$ Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + (c \cdot 0)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}} \right)^2 + Q \right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)} \right)} \right) - c \cdot 0 = 18.8\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$p_{max} := u + p'_{max} = 18.8\ psi$ Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

$D_{PT} := 3.5\ in$ Pilot tube diameter

$D_0 := 9.5\ in$ Initial borehole diameter for pilot tube

$h := 25.2\ ft$ Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 70\ pcf$ Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 12.3\ psi$ Minimum required mud pressure to overcome differntial head

$Q_f := 200\ gpm$ Assumed mud flow rate

$\tau_o := 16\ \frac{lbf}{100 \cdot ft^2}$ Assumed yield point of mud per 100 square feet

$\mu_{pl} := 25 \cdot \frac{poise}{100}$ Assumed plastic viscosity of mud

$$v := \frac{Q_f}{0.785\left(D_0^{\ 2} - D_{PT}^{\ 2}\right)} = 62.9\ \frac{ft}{min}$$ Computed mud flow velocity

$L_{total} = 556.5\ ft$ Total length of HDD crossing

$$p_2 := L_{total} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2} \right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)} \right) \right) = 1.2\ psi$$

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 13.5\ psi$ Minimum required mud pressure

$check := \text{if}\left(p_{max} > p_{min.}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

D1.1 - Overburden Pressure (Considering Deformed Borehole with Arching Mobilized)

$H_c := H_{max} = 23.8\ ft$ Depth of cover

$\phi = 0\ deg$ Friction angle of soil

$B := D_r = 18\ in$ "Silo" width, conservative value = reamed hole diameter

$K := \tan\left(45 - \frac{\phi}{2}\right)^2$ Earth pressure coefficient

$\gamma = 100\ pcf$ Unit weight of soil, assumed

$$k := \frac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)\right)}{\boxed{2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)}} = ?\ k := 1$$

Arching factor (Eq. 6, p.432, PPI)

$P_E := k \cdot (\gamma - \gamma_m) \cdot (H_c) = 5\ psi$ Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

$E_{short} := 57500 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)

$$k_{short} := \frac{E_{short}}{12 \cdot (DR_1 - 1)^3} = 9.36\ psi$$

Variable in earth load deflection equation

$$\Delta y_{ELD\_short} := \frac{0.0125 \cdot P_E}{k_{short}} = 0.7\%$$

Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437, PPI Handbook)

D1.3 Earth Load Deflection (Long Term)

$E_{long} := 28200 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$$k := \frac{E_{long}}{12 \cdot (DR_1 - 1)^3} = 4.6\ psi$$

Variable in earth load deflection equation

$$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 1.4\%$$

Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437)

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

$D_1 = 10.75\ in$ — Outside diameter of casing pipe

$t := T_{p1} = 1.194\ in$ — Thickness of casing pipe

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit (Table B.1.1)

$\gamma_m = 70\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

$I := \frac{t^3}{12} = 0.14\ \frac{in^4}{in}$ — Moment of inertia of pipe wall cross section

$$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.0$$

Pipe ring deflection to buoyant force ASTM F 1962 (Eq. X2.6, p.6)

D2.1 Buoyant Deflection (Long Term)

Please note that long term buoyant deflection was assumed negibile, since grout is assumed to be cured after a 1-week period from installation/pumping.

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{short}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.0000033$$

Deflection due to longitudinal bending

$$\Delta y_{R\_short} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material at long term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{long}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.000003$$

Deflection due to longitudinal bending

$$\Delta y_{R\_long} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

$\Delta y_{lim} := 7.5\%$

Deflection limit for DR 9 non pressurized pipe (Table 2 , p. 437, PPI Handbook)

D4.1 - Net Short Term

$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 0.7\%$

Percent ring deflection in short term analysis

$Check := \text{if}\left(\Delta y_{short\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 1.4\%$

Percent ring deflection in long term analysis (50 years)

$Check := \text{if}\left(\Delta y_{long\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5 - Unconstrained Ring Buckling

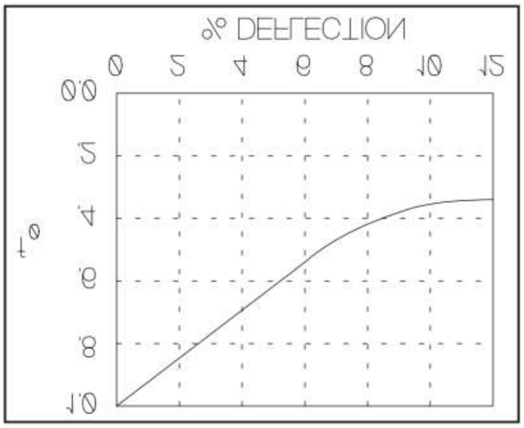
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ — Factor of Safety

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)



Ovality compensation factor, Figure 3 (PPI Chp. 12). Calculated deflection limit in section D4.1

$f_{o\_short} := 0.98$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1-\mu_{short}^{2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_short}}{N} = 125.4\ psi$$

Allowable unconstrained buckling pressure

$H = 25.2\ ft$ — Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 12.25\ psi$ — Pressure of drilling slurry

$P_{net} := P_{mud} = 12.25\ psi$ — Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_short} > P_{net}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5.2 - Unconstrained Ring Buckling, Levy's Equation (Long Term)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ — Factor of Safety

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material, long term (ASTM F 1962, 8.2.4.2)

$E_{long} = 28200\ psi$

Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$f_{o\_long} := 0.45$

Ovality compensation factor, Figure 3 (PPI Chp. 12). Use deflection limit calculated in Section D4.2

$$P_{UC\_long} := \left(\frac{2 \cdot E_{long}}{1 - {\mu_{long}}^2}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_long}}{N} = 31.1\ psi$$

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 0\ psi$

Groundwater head pressure

$P_{net} := P_{GW}$

Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_long} > P_{net}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

References

1. ASTM F 1962 -05 Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings

2. ASTM F 1804-08 Standard Practice for Determining Allowable Tensile Load for Polyethylene (PE) Gas Pipe During Pull-In Installation

3. Mohammad Najafi, 2013, Trenchless Technology, First Edition, McGraw Hill

4. Larry Slavin, 2009, Guidelines for Use of Mini-Horizontal Direction Drilling for Placement of High Density Polyethylene Pipe

5. Handbook of Polyethylete Pipe, 2008, Plastics Pipe Institute (PPI), Second Edition

Defining Parameters of Horizontal Directional Drilling :

$D_1 := 10.75\ in$	Pipe 1 outer diameter
$D_2 := 2.375\ in$	Pipe 2 outer diameter
$D_{rod} := 3.5\ in$	Assumed drill rod diameter
$DR_1 := 9$	Dimension ratio of Pipe 1
$DR_2 := 11$	Dimension ratio of Pipe 2
$T_{p1} := \frac{D_1}{DR_1} = 1.194\ in$	Thickness of Pipe 1
$T_{p2} := \frac{D_2}{DR_2} = 0.216\ in$	Thickness of Pipe 2
$C_1 := \pi \cdot D_1 = 33.8\ in$	Pipe circumference of pipe 1
$C_2 := \pi \cdot D_2 = 7.5\ in$	Pipe circumference of pipe 2

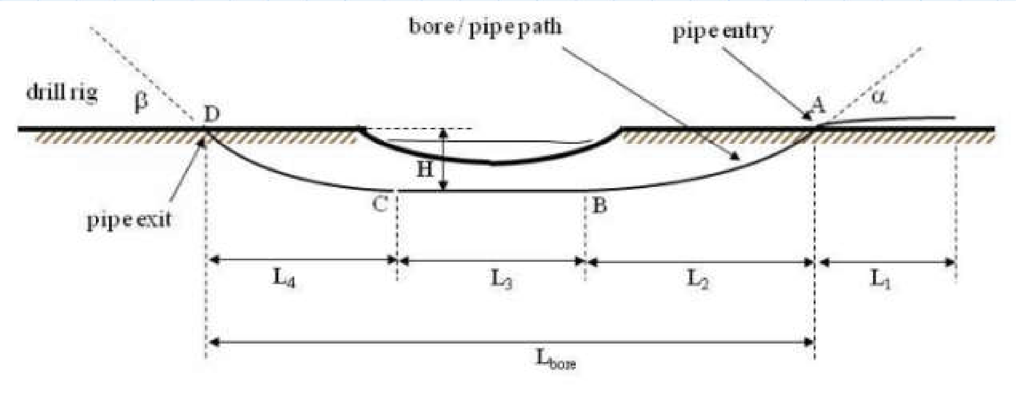


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 8\ °$ $\quad \alpha_{in} := \alpha = 0.1396\ rad$	Borehole entry angle (degrees, radians)
$\beta := 10\ °$ $\quad \beta_{exit} := \beta = 0.1745\ rad$	Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$	Final reamed bore diameter
$H_{max} := 30.9\ ft$	Max depth of bore hole to final reamed bore diameter
$H_{max1} := H_{max} + \frac{D_r}{2} = 31.65\ ft$	Max depth to bore hole springline from ground surface
$L_{total} := 1155.8\ ft$	Total length of HDD crossing
$L_1 := 150\ ft$	Assumed pipe drag on surface, See Illustration 1
$L_2 := 337.7\ ft$	Horizontal length to achieve depth - provided by Contractor, See Illustration 1
$L_3 := 668.2\ ft$	Straight horizontal section
$L_4 := 149.9\ ft$	Horizontal distance to rise to surface, See Illustration 1
$H := 25.5\ ft$	Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1

$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 70\ pcf$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.1$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

$R_{avg.\_in} := 1000\ ft$	Radius of curvature at the entry, provided by Contractor
$R_{avg.\_out} := 1000\ ft$	Radius of curvature at the exit, provided by Contractor
$R := \frac{R_{avg.\_in} + R_{avg.\_out}}{2} = 1000\ ft$	Average radius of curvature at entry
$r_{rod} := 1200 \cdot D_{rod} = 350\ ft$	ASTM F 1962-99, Equation 1, p7

$Check := \text{if}\left(R_{avg.\_in} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

$Check := \text{if}\left(R_{avg.\_out} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

Radius of curvature should exceed 40 times the pipe outside diameter to prevent ring collapse.

$e_a := \frac{D_1}{2 \cdot R} = 0.0004$	Strain within the casing pipe
$E_{12hr} := 57500 \cdot psi$	Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)
$S_a := e_a \cdot E_{12hr} = 25.8\ psi$	Axial bending stress within the casing pipe

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

$$w_a := \frac{\pi}{4}\left(\left({D_1}^2-\left(D_1-T_{p1}\right)^2\right)+\left({D_2}^2-\left(D_2-T_{p2}\right)^2\right)\right)\cdot\rho_w\cdot\gamma_a = 8.3\ plf$$

Effective weight

B1.2 - Upward Buoyant Force:

$$w_b := \left(\frac{\pi\cdot\left({D_1}^2+{D_2}^2\right)}{4}\right)\rho_w\cdot\gamma_b - w_a = 38\ plf$$

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

$$\Delta T := \Delta P\cdot\left(\frac{\pi}{8}\right)\left({D_r}^2-\left({D_1}^2+{D_2}^2\right)\right) = 796\ lbf$$

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a\cdot\alpha_{in}}\cdot\left(v_a\cdot w_a\cdot\left(L_1+L_2+L_3+L_4\right)\right) = 1097\ lbf$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b\cdot\alpha_{in}}\left(T_a+v_b\cdot\left|w_b\right|\cdot L_2+w_b\cdot H_{max}-v_a\cdot w_a\cdot L_2\cdot e^{\left(v_a\cdot\alpha_{in}\right)}\right) = 6085\ lbf$$

Pullback force increase with depth

B1.6 - Pullback Force Point C:

$$T_c := T_b+\left(v_b\cdot w_b\cdot L_3\right)-e^{\left(v_b\cdot\alpha_{in}\right)}\cdot\left(v_a\cdot w_a\cdot L_3\cdot e^{\left(v_a\cdot\alpha_{in}\right)}\right) = 13115\ lbf$$

B1.7 - Pullback Force at D:

$$T_d := e^{\left(v_b\cdot\beta_{exit}\right)}\cdot\left(T_c+v_b\cdot\left|w_b\right|\cdot L_4-w_b\cdot H_{max}-e^{\left(v_a\cdot\alpha_{in}\right)}\cdot\left(v_a\cdot w_a\cdot L_4\cdot e^{\left(v_a\cdot\alpha_{in}\right)}\right)\right) = 14248\ lbf$$

B1.8 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_c, T_d\right)+\Delta T = 15045\ lbf$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi\cdot{D_1}^2\right)}{4}\right)\cdot\rho_w\cdot\left(\gamma_b-\gamma_c\cdot\left(1-\left(\frac{2}{DR_1}\right)\right)^2\right)-w_a = 12\ plf$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a\cdot\alpha_{in}}\cdot\left(v_a\cdot w_a\cdot\left(L_1+L_2+L_3+L_4\right)\right) = 1097\ lbf$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot |w_{bfilled}| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 3100\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C:

$$T_{cfilled} := T_{bfilled} + \left(v_b \cdot |w_{bfilled}| \cdot L_3\right) - e^{(v_b \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 4928\ lbf$$

B2.5 - Pullback Force at D:

$$T_{dfilled} := e^{(v_b \cdot \beta_{exit})} \cdot \left(T_{cfilled} + v_b \cdot |w_{bfilled}| \cdot L_4 - e^{(v_a \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{(v_a \cdot \alpha_{in})}\right)\right) = 5629\ lbf$$

B2.6 - Maximum Pullback Force - Filled Pipe with Water:

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{cfilled}, T_{dfilled}\right) = 5629\ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

$$A_1 := \frac{\pi}{4}\left(D_1^2 - \left(D_1 - T_{p1}\right)^2\right) = 19\ in^2$$ Cross-sectional area of Pipe 1

$$A_2 := \frac{\pi}{4}\left(D_2^2 - \left(D_2 - T_{p2}\right)^2\right) = 0.8\ in^2$$ Cross-sectional area of Pipe 2

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 14461\ lbf$$ Pullback forces acting on Pipe 1 (Empty)

$$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 584\ lbf$$ Pullback forces acting on Pipe 2 (Empty)

$$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 5411\ lbf$$ Pullback forces acting on Pipe 1 (Ballast)

$$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 218\ lbf$$ Pullback forces acting on Pipe 2 (Ballast)

$$P_{SPF1} := 41214\ lbf$$ Safe pullback forces Pipe 1 (Table %, p. 448, PPI)

$$P_{SPF2} := 1683\ lbf$$ Safe pullback forces Pipe 2 (Table %, p. 448, PPI)

$$check := \text{if}\left(P_{SPF1} > P_{11}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$$
$$check := \text{if}\left(P_{SPF2} > P_{21}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$$
$$check := \text{if}\left(P_{SPF1} > P_{12}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$$
$$check := \text{if}\left(P_{SPF2} > P_{22}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$$

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

-MathCAD calculations are used for a critical structure as identified for each crossing. If the HDD alignment crosses multiple structures the one with least cover was used. Provided hydrofracture graphs use equations, as detailed herein, to identify potential frac-out areas. Typically entry and exit areas are most susceptible to frac-out due to low cover.

-Where applicable, soil properties referenced from Kiewit's Proposed Soil Properties for CHPE Package 1, dated October 12, 2022.

$H_w := 0 \cdot ft$ — Depth of the bore below groundwater elevation

$H_c := 25.6\ ft$ — Vertical separation distance between critical structure and pipe (~3+50)

$\gamma := 110\ pcf$ — Assumed unit weight soft to clay/silt (N = 7 to 16; med. stiff clay)

$\gamma_w := 62.4\ pcf$ — Unit weight of water

$\gamma' := \gamma - \gamma_w = 47.6\ pcf$ — Effective unit weight

$u := \gamma_w \cdot H_w = 0\ psi$ — Initial pore water pressure

$\phi := 0\ deg$ — Assumed friction Angle

$c := 800\ psf = 5.56\ psi$ — Assumed cohesion of encountered material

$R_0 := \frac{D_{rod}}{2} = 1.75\ in$ — Initial radius of the borehole

$R_{pmax} := \frac{1}{2} \cdot H_c = 13\ ft$ — Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := (\gamma \cdot (H_c - H_w)) + \gamma' \cdot H_w = 20\ psi$ — Initial effective stress

Table C.2 Typical values of modulus of elasticity (E_S) for different types of soils

Type of Soil	E_s (N/mm^2)
Clay	
Very soft	2–15
Soft	5–25
Medium	15–50
Hard	50–100
Sandy	25–250
Glacial till	
Loose	10–153
Dense	144–720
Very dense	478–1,440
Loess	14–57
Sand	
Silty	7–21
Loose	10–24
Dense	48–81
Sand and gravel	
Loose	48–148
Dense	96–192
Shale	144–14,400
Silt	2–20

$E_s := 15\ \frac{N}{mm^2} = 2176\ psi$

Assumed modulus of elasticity

Table C.4 Typical values of Poisson's ratio (μ) for soils

Type of soil	μ
Clay (saturated)	0.4 – 0.5
Clay (unsaturated)	0.1 – 0.3
Sandy clay	0.2 – 0.3
Silt	0.3 – 0.35
Sand (dense)	0.2 – 0.4
Course (void ratio = 0.4 – 0.7)	0.15
Fine grained (void ratio = 0.4 – 0.7)	0.25
Rock	0.1–0.4 (depends on type of rock)
Loess	0.1 – 0.3
Ice	0.36
Concrete	0.15

$\nu_s := 0.5$

Poissions ratio of material encountered

$$G := \frac{E_s}{2\left(1+\nu_s\right)} = 725\ psi$$ Shear modulus of soil

$$Q := \frac{\left(\sigma'_0 \cdot \sin(\phi)\right) + (c \cdot 0)}{G} = 0$$

Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot (1+\sin(\phi)) + c \cdot \cos(\phi) = 25.1\ psi$$

Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + (c \cdot 0)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot 0 = 25.1\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$p_{max} := u + p'_{max} = 25.1\ psi$ Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

$D_{PT} := 5\ in$ Pilot tube diameter

$D_0 := 9.5\ in$ Initial borehole diameter for pilot tube

$h := 25.6\ ft$ Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 70\ pcf$ Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 12.4\ psi$ Minimum required mud pressure to overcome differntial head

$Q_f := 200\ gpm$ Assumed mud flow rate

$$\tau_o := 16\ \frac{lbf}{100 \cdot ft^2}$$ Assumed yield point of mud per 100 square feet

$$\mu_{pl} := 25 \cdot \frac{poise}{100}$$ Assumed plastic viscosity of mud

$$v := \frac{Q_f}{0.785\left(D_0^{\ 2} - D_{PT}^{\ 2}\right)} = 75.2\ \frac{ft}{min}$$ Computed mud flow velocity

$L_{structure} := 350\ ft$ Length to sturcture

$$p_2 := L_{structure} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2} \right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)} \right) \right) = 1\ psi$$

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 13.5\ psi$ Minimum required mud pressure

$check := \mathbf{if}\left(p_{max} > p_{min.}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

D1.1 - Overburden Pressure (Considering Deformed Borehole with Arching Mobilized)

$H_c := H_{max} = 30.9\ ft$ Depth of cover

$\phi = 0\ deg$ Friction angle of soil

$B := D_r = 18\ in$ "Silo" width, conservative value = reamed hole diameter

$K := \tan\left(45 - \frac{\phi}{2}\right)^2$ Earth pressure coefficient

$\gamma = 110\ pcf$ Unit weight of soil, assumed

$$k := \frac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)\right)}{\boxed{2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)}} = ?\quad k := 1$$

Arching factor (Eq. 6, p.432, PPI)

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 10\ psi \quad P_E = 1471\ psf$ Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

$E_{short} := 57500 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)

$$k_{short} := \frac{E_{short}}{12 \cdot (DR_1 - 1)^3} = 9.36\ psi$$

Variable in earth load deflection equation

$$\Delta y_{ELD\_short} := \frac{0.0125 \cdot P_E}{k_{short}} = 1.4\%$$

Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437, PPI Handbook)

D1.3 Earth Load Deflection (Long Term)

$E_{long} := 28200 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$$k := \frac{E_{long}}{12 \cdot (DR_1 - 1)^3} = 4.6\ psi$$

Variable in earth load deflection equation

$$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 2.8\%$$

Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437)

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

$D_1 = 10.75\ in$ — Outside diameter of casing pipe

$t := T_{p1} = 1.194\ in$ — Thickness of casing pipe

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit (Table B.1.1)

$\gamma_m = 70\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

$I := \frac{t^3}{12} = 0.14\ \frac{in^4}{in}$ — Moment of inertia of pipe wall cross section

$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.0$ — Pipe ring deflection to buoyant force ASTM F 1962 (Eq. X2.6, p.6)

D2.1 Buoyant Deflection (Long Term)

Please note that long term buoyant deflection was assumed negibile, since grout is assumed to be cured after a 1-week period from installation/pumping.

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{short}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.0000033$ — Deflection due to longitudinal bending

$\Delta y_{R\_short} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$ — Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material at long term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{long}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.000003$ — Deflection due to longitudinal bending

$\Delta y_{R\_long} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$ — Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

$\Delta y_{lim} := 7.5\%$

Deflection limit for DR 9 non pressurized pipe (Table 2 , p. 437, PPI Handbook)

D4.1 - Net Short Term

$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 1.4\%$

Percent ring deflection in short term analysis

$Check := \text{if}\left(\Delta y_{short\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 2.8\%$

Percent ring deflection in long term analysis (50 years)

$Check := \text{if}\left(\Delta y_{long\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5 - Unconstrained Ring Buckling

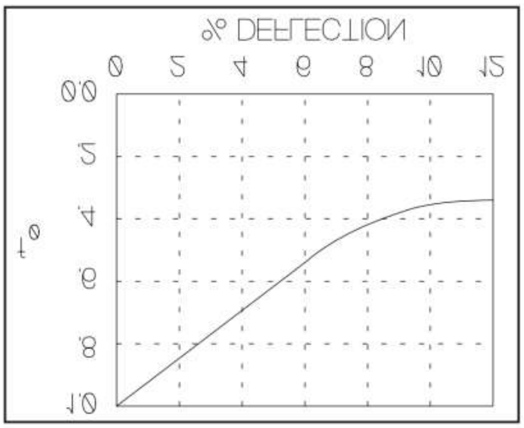
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ Factor of Safety

$\mu_{short} := 0.35$ Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$E_{short} = 57500\ psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)



Ovality compensation factor, Figure 3 (PPI Chp. 12). Calculated deflection limit in section D4.1

$f_{o\_short} := 0.87$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1 - \mu_{short}^{2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_short}}{N} = 111.3\ psi$$ Allowable unconstrained buckling pressure

$H = 25.5\ ft$ Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 12.4\ psi$ Pressure of drilling slurry

$P_{net} := P_{mud} = 12.4\ psi$ Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_short} > P_{net}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5.2 - Unconstrained Ring Buckling, Levy's Equation (Long Term)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ Factor of Safety

$\mu_{long} := 0.45$ Poisson's Ratio for PE pipe material, long term (ASTM F 1962, 8.2.4.2)

$E_{long} = 28200\ psi$

Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$f_{o\_long} := 0.45$

Ovality compensation factor, Figure 3 (PPI Chp. 12). Use deflection limit calculated in Section D4.2

$$P_{UC\_long} := \left(\frac{2 \cdot E_{long}}{1 - \mu_{long}^{\ 2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_long}}{N} = 31.1\ psi$$

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 0\ psi$

Groundwater head pressure

$P_{net} := P_{GW}$

Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_long} > P_{net}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$

References

1. ASTM F 1962 -05 Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings
2. ASTM F 1804-08 Standard Practice for Determining Allowable Tensile Load for Polyethylene (PE) Gas Pipe During Pull-In Installation
3. Proposed Soil Properties for CHPE Package 1 HDDs, Kiewit, October 12, 2022.
4. Handbook of Polyethylete Pipe, 2008, Plastics Pipe Institute (PPI), Second Edition
5. Larry Slavin, 2009, Guidelines for Use of Mini-Horizontal Direction Drilling for Placement of High Density Polyethylene Pipe
6. Mohammad Najafi, 2013, Trenchless Technology, First Edition, McGraw Hill

Defining Parameters of Horizontal Directional Drilling :

$D_1 := 10.75\ in$ Pipe 1 outer diameter

$D_2 := 2.375\ in$ Pipe 2 outer diameter

$D_{rod} := 3.5\ in$ Assumed drill rod diameter

$DR_1 := 9$ Dimension ratio of Pipe 1

$DR_2 := 11$ Dimension ratio of Pipe 2

$T_{p1} := \frac{D_1}{DR_1} = 1.194\ in$ Thickness of Pipe 1

$T_{p2} := \frac{D_2}{DR_2} = 0.216\ in$ Thickness of Pipe 2

$C_1 := \pi \cdot D_1 = 33.8\ in$ Pipe circumference of pipe 1

$C_2 := \pi \cdot D_2 = 7.5\ in$ Pipe circumference of pipe 2

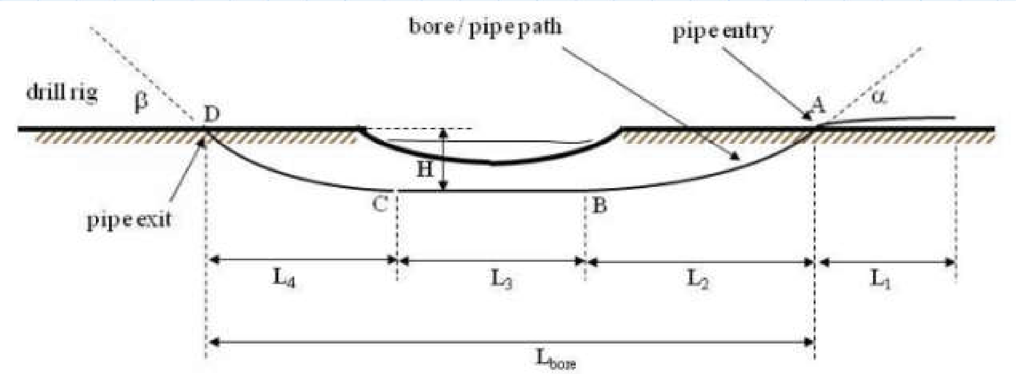


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 8\ °$ $\alpha_{in} := \alpha = 0.1396\ rad$ Borehole entry angle (degrees, radians)

$\beta := 10\ °$ $\beta_{exit} := \beta = 0.1745\ rad$ Borehole exit angle (degrees, radians)

$D_r := 18 \cdot in$ Final reamed bore diameter

$H_{max} := 30.9\ ft$ Max depth of bore hole to final reamed bore diameter

$H_{max1} := H_{max} + \frac{D_r}{2} = 31.65\ ft$ Max depth to bore hole springline from ground surface

$L_{total} := 1132.7\ ft$ Total length of HDD crossing

$L_1 := 150\ ft$ Assumed pipe drag on surface, See Illustration 1

$L_2 := 283.7\ ft$ Horizontal length to achieve depth - provided by Contractor, See Illustration 1

$L_3 := 617.0\ ft$ Straight horizontal section

$L_4 := 232.8\ ft$ Horizontal distance to rise to surface, See Illustration 1

$H := 25.3\ ft$ Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1

$v_a := 0.1$ — Friction coefficient before pipe enters (rollers assumed)

$v_b := 0.3$ — Friction coefficient for the bundle within borehole (lubrication assumed)

$\rho_w := 62.4\ pcf$ — Unit weight of water

$\gamma_a := 0.965$ — Specific gravity of pipe

$\gamma_m := 90\ pcf$ — Assumed unit weight of slurry

$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.4$ — Specific gravity of slurry, assumed unit weight

$\gamma_c := 1.0$ — Specific gravity of water to fill the pipe

$\Delta P := 10\ psi$ — Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)

$g := 32.2\ \frac{ft}{s^2}$ — Gravitational Constant

A - Axial Bending Stress:

$R_{avg.\_in} := 1000\ ft$ — Radius of curvature at the entry, provided by Contractor

$R_{avg.\_out} := 1000\ ft$ — Radius of curvature at the exit, provided by Contractor

$R := \frac{R_{avg.\_in} + R_{avg.\_out}}{2} = 1000\ ft$ — Average radius of curvature at entry

$r_{rod} := 1200 \cdot D_{rod} = 350\ ft$ — ASTM F 1962-99, Equation 1, p7

$Check := \text{if}\left(R_{avg.\_in} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

$Check := \text{if}\left(R_{avg.\_out} > r_{rod}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

Radius of curvature should exceed 40 times the pipe outside diameter to prevent ring collapse.

$e_a := \frac{D_1}{2 \cdot R} = 0.0004$ — Strain within the casing pipe

$E_{12hr} := 57500 \cdot psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)

$S_a := e_a \cdot E_{12hr} = 25.8\ psi$ — Axial bending stress within the casing pipe

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

$$w_a := \frac{\pi}{4}\left(\left({D_1}^2-\left(D_1-T_{p1}\right)^2\right)+\left({D_2}^2-\left(D_2-T_{p2}\right)^2\right)\right)\cdot\rho_w\cdot\gamma_a = 8.3\ plf$$

Effective weight

B1.2 - Upward Buoyant Force:

$$w_b := \left(\frac{\pi\cdot\left({D_1}^2+{D_2}^2\right)}{4}\right)\rho_w\cdot\gamma_b - w_a = 51.2\ plf$$

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

$$\Delta T := \Delta P\cdot\left(\frac{\pi}{8}\right)\left({D_r}^2-\left({D_1}^2+{D_2}^2\right)\right) = 796\ lbf$$

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a\cdot\alpha_{in}}\cdot\left(v_a\cdot w_a\cdot\left(L_1+L_2+L_3+L_4\right)\right) = 1079\ lbf$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b\cdot\alpha_{in}}\left(T_a+v_b\cdot\left|w_b\right|\cdot L_2+w_b\cdot H_{max}-v_a\cdot w_a\cdot L_2\cdot e^{\left(v_a\cdot\alpha_{in}\right)}\right) = 7071\ lbf$$

Pullback force increase with depth

B1.6 - Pullback Force Point C:

$$T_c := T_b+\left(v_b\cdot w_b\cdot L_3\right)-e^{\left(v_b\cdot\alpha_{in}\right)}\cdot\left(v_a\cdot w_a\cdot L_3\cdot e^{\left(v_a\cdot\alpha_{in}\right)}\right) = 16009\ lbf$$

B1.7 - Pullback Force at D:

$$T_d := e^{\left(v_b\cdot\beta_{exit}\right)}\cdot\left(T_c+v_b\cdot\left|w_b\right|\cdot L_4-w_b\cdot H_{max}-e^{\left(v_a\cdot\alpha_{in}\right)}\cdot\left(v_a\cdot w_a\cdot L_4\cdot e^{\left(v_a\cdot\alpha_{in}\right)}\right)\right) = 18762\ lbf$$

B1.8 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_c, T_d\right)+\Delta T = 19558\ lbf$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi\cdot{D_1}^2\right)}{4}\right)\cdot\rho_w\cdot\left(\gamma_b-\gamma_c\cdot\left(1-\left(\frac{2}{DR_1}\right)\right)^2\right)-w_a = 24.6\ plf$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a\cdot\alpha_{in}}\cdot\left(v_a\cdot w_a\cdot\left(L_1+L_2+L_3+L_4\right)\right) = 1079\ lbf$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 4355 \ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C:

$$T_{cfilled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_3\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 8376 \ lbf$$

B2.5 - Pullback Force at D:

$$T_{dfilled} := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{cfilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 10432 \ lbf$$

B2.6 - Maximum Pullback Force - Filled Pipe with Water:

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{cfilled}, T_{dfilled}\right) = 10432 \ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

$$A_1 := \frac{\pi}{4}\left(D_1^{\,2} - \left(D_1 - T_{p1}\right)^2\right) = 19 \ in^2$$ Cross-sectional area of Pipe 1

$$A_2 := \frac{\pi}{4}\left(D_2^{\,2} - \left(D_2 - T_{p2}\right)^2\right) = 0.8 \ in^2$$ Cross-sectional area of Pipe 2

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 18799 \ lbf$$ Pullback forces acting on Pipe 1 (Empty)

$$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 759 \ lbf$$ Pullback forces acting on Pipe 2 (Empty)

$$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 10027 \ lbf$$ Pullback forces acting on Pipe 1 (Ballast)

$$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 405 \ lbf$$ Pullback forces acting on Pipe 2 (Ballast)

$$P_{SPF1} := 41214 \ lbf$$ Safe pullback forces Pipe 1 (Table %, p. 448, PPI)

$$P_{SPF2} := 1683 \ lbf$$ Safe pullback forces Pipe 2 (Table %, p. 448, PPI)

$$check := \text{if}\left(P_{SPF1} > P_{11}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$
$$check := \text{if}\left(P_{SPF2} > P_{21}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$
$$check := \text{if}\left(P_{SPF1} > P_{12}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$
$$check := \text{if}\left(P_{SPF2} > P_{22}, \text{"okay"}, \text{"not okay"}\right) = \text{"okay"}$$

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

-MathCAD calculations are used for a critical structure as identified for each crossing. If the HDD alignment crosses multiple structures the one with least cover was used. Provided hydrofracture graphs use equations, as detailed herein, to identify potential frac-out areas. Typically entry and exit areas are most susceptible to frac-out due to low cover.

-Where applicable, soil properties referenced from Kiewit's Proposed Soil Properties for CHPE Package 1, dated October 12, 2022.

$H_w := 0 \cdot ft$ Depth of the bore below groundwater elevation

$H_c := 22.0\ ft$ Vertical separation distance between critical structure and pipe (Schohaire Tkpe controls)

$\gamma := 100\ pcf$ Assumed unit weight soft to clay/silt (zero blow count material)

$\gamma_w := 62.4\ pcf$ Unit weight of water

$\gamma' := \gamma - \gamma_w = 37.6\ pcf$ Effective unit weight

$u := \gamma_w \cdot H_w = 0\ psi$ Initial pore water pressure

$\phi := 0\ deg$ Assumed friction Angle

$c := 450\ psf = 3.13\ psi$ Assumed cohesion of encountered material

$R_0 := \frac{D_{rod}}{2} = 1.75\ in$ Initial radius of the borehole

$R_{pmax} := \frac{1}{2} \cdot H_c = 11\ ft$ Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := \left(\left(\gamma \cdot \left(H_c - H_w\right)\right) + \gamma' \cdot H_w\right) = 15\ psi$ Initial effective stress

Table C.2 Typical values of modulus of elasticity (E_S) for different types of soils

Type of Soil	E_s (N/mm^2)
Clay	
Very soft	2–15
Soft	5–25
Medium	15–50
Hard	50–100
Sandy	25–250
Glacial till	
Loose	10–153
Dense	144–720
Very dense	478–1,440
Loess	14–57
Sand	
Silty	7–21
Loose	10–24
Dense	48–81
Sand and gravel	
Loose	48–148
Dense	96–192
Shale	144–14,400
Silt	2–20

$E_s := 5\ \frac{N}{mm^2} = 725\ psi$

Assumed modulus of elasticity

Table C.4 Typical values of Poisson's ratio (μ) for soils

Type of soil	μ
Clay (saturated)	0.4 – 0.5
Clay (unsaturated)	0.1 – 0.3
Sandy clay	0.2 – 0.3
Silt	0.3 – 0.35
Sand (dense)	0.2 – 0.4
Course (void ratio = 0.4 – 0.7)	0.15
Fine grained (void ratio = 0.4 – 0.7)	0.25
Rock	0.1–0.4 (depends on type of rock)
Loess	0.1 – 0.3
Ice	0.36
Concrete	0.15

$\nu_s := 0.4$ Poissions ratio of material encountered

$$G := \frac{E_s}{2\,(1+\nu_s)} = 259\ psi$$ Shear modulus of soil

$$Q := \frac{(\sigma'_0 \cdot \sin(\phi)) + (c \cdot 0)}{G} = 0$$ Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot (1+\sin(\phi)) + c \cdot \cos(\phi) = 18.4\ psi$$ Mud pressure at which the first plastic deformation takes place

$$p'_{max} := (p'_f + (c \cdot 0)) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}} \right)^2 + Q \right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)} \right)} \right) - c \cdot 0 = 18.4\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$$p_{max} := u + p'_{max} = 18.4\ psi$$ Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

$D_{PT} := 5\ in$ Pilot tube diameter

$D_0 := 9.5\ in$ Initial borehole diameter for pilot tube

$h := 18.85\ ft$ Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 90\ pcf$ Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 11.8\ psi$ Minimum required mud pressure to overcome differntial head

$Q_f := 200\ gpm$ Assumed mud flow rate

$\tau_o := 16\ \frac{lbf}{100 \cdot ft^2}$ Assumed yield point of mud per 100 square feet

$\mu_{pl} := 25 \cdot \frac{poise}{100}$ Assumed plastic viscosity of mud

$$v := \frac{Q_f}{0.785\,(D_0^{\,2} - D_{PT}^{\,2})} = 75.2\ \frac{ft}{min}$$ Computed mud flow velocity

$L_{structure} := 125\ ft$ — Length to sturcture

$$p_2 := L_{structure} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2} \right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)} \right) \right) = 0.4\ psi$$

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 12.2\ psi$ — Minimum required mud pressure

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

D1.1 - Overburden Pressure (Considering Deformed Borehole with Arching Mobilized)

$H_c := H_{max} = 30.9\ ft$ Depth of cover

$\phi = 0\ deg$ Friction angle of soil

$B := D_r = 18\ in$ "Silo" width, conservative value = reamed hole diameter

$K := \tan\left(45 - \frac{\phi}{2}\right)^2$ Earth pressure coefficient

$\gamma = 100\ pcf$ Unit weight of soil, assumed

$$k := \frac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)\right)}{\boxed{2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)}} = ?\quad k := 1$$

Arching factor (Eq. 6, p.432, PPI)

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 8\ psi \quad P_E = 1162\ psf$ Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

$E_{short} := 57500 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)

$$k_{short} := \frac{E_{short}}{12 \cdot (DR_1 - 1)^3} = 9.36\ psi$$

Variable in earth load deflection equation

$$\Delta y_{ELD\_short} := \frac{0.0125 \cdot P_E}{k_{short}} = 1.1\%$$

Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437, PPI Handbook)

D1.3 Earth Load Deflection (Long Term)

$E_{long} := 28200 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$$k := \frac{E_{long}}{12 \cdot (DR_1 - 1)^3} = 4.6\ psi$$

Variable in earth load deflection equation

$$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 2.2\%$$

Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437)

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

$D_1 = 10.75\ in$ — Outside diameter of casing pipe

$t := T_{p1} = 1.194\ in$ — Thickness of casing pipe

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 Fahrenheit (Table B.1.1)

$\gamma_m = 90\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

$I := \frac{t^3}{12} = 0.14\ \frac{in^4}{in}$ — Moment of inertia of pipe wall cross section

$$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.1\%$$

Pipe ring deflection to buoyant force ASTM F 1962 (Eq. X2.6, p.6)

D2.1 Buoyant Deflection (Long Term)

Please note that long term buoyant deflection was assumed negibile, since grout is assumed to be cured after a 1-week period from installation/pumping.

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{short}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.0000033$$

Deflection due to longitudinal bending

$$\Delta y_{R\_short} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material at long term (ASTM F 1962, 8.2.4.2)

$R = 1000\ ft$ — Radius of curvature

$$z := \frac{\frac{3}{2} \cdot \left(1 - {\mu_{long}}^2\right) \left(D_1 - t\right)^4}{16 \cdot t^2 \cdot R^2} = 0.000003$$

Deflection due to longitudinal bending

$$\Delta y_{R\_long} := \left(\frac{2}{3}\right) \cdot z + \left(\frac{71}{135}\right) \cdot z^2 = 0.0002\%$$

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

$\Delta y_{lim} := 7.5\%$

Deflection limit for DR 9 non pressurized pipe (Table 2 , p. 437, PPI Handbook)

D4.1 - Net Short Term

$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 1.1\%$

Percent ring deflection in short term analysis

$Check := \text{if}\left(\Delta y_{short\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 2.2\%$

Percent ring deflection in long term analysis (50 years)

$Check := \text{if}\left(\Delta y_{long\_net} < \Delta y_{lim}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5 - Unconstrained Ring Buckling

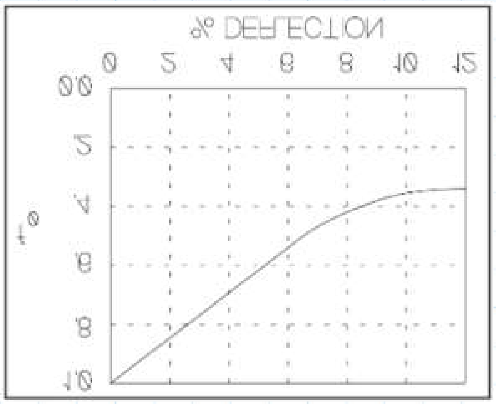
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ — Factor of Safety

$\mu_{short} := 0.35$ — Poisson's Ratio for PE pipe material at short term (ASTM F 1962, 8.2.4.2)

$E_{short} = 57500\ psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)



Ovality compensation factor, Figure 3 (PPI Chp. 12). Calculated deflection limit in section D4.1

$f_{o\_short} := 0.92$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1-\mu_{short}^{2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_short}}{N} = 117.7\ psi$$

Allowable unconstrained buckling pressure

$H = 25.3\ ft$ — Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 15.81\ psi$ — Pressure of drilling slurry

$P_{net} := P_{mud} = 15.81\ psi$ — Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_short} > P_{net}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

D5.2 - Unconstrained Ring Buckling, Levy's Equation (Long Term)

Note that constraining the pipe will increase the pipe's buckling strength, therefore considering an unconstrained condition will produce a conservative value.

$N := 2.0$ — Factor of Safety

$\mu_{long} := 0.45$ — Poisson's Ratio for PE pipe material, long term (ASTM F 1962, 8.2.4.2)

$E_{long} = 28200\ psi$

Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 50 years of sustained loading (Table X1.1 ASTM F 1962)

$f_{o\_long} := 0.45$

Ovality compensation factor, Figure 3 (PPI Chp. 12). Use deflection limit calculated in Section D4.2

$$P_{UC\_long} := \left(\frac{2 \cdot E_{long}}{1 - \mu_{long}^{\ 2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_long}}{N} = 31.1\ psi$$

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 0\ psi$

Groundwater head pressure

$P_{net} := P_{GW}$

Net external loading with open borehole

$Check := \text{if}\left(P_{UC\_long} > P_{net}, \text{“okay”}, \text{“not okay”}\right) = \text{“okay”}$

References

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