INTRODUCTION

The purpose of this structural design guide is to illustrate application of the thermoplastic pipe structural design process for typical culvert and storm drain designs. The design examples use the methodology detailed in the Structural Design chapter of the PPI Drainage Handbook, which follows the current AASHTO LRFD Bridge Design Specifications (AASHTO) Section 12.12 provisions for thermoplastic pipe design as well as peer reviewed research. Refer to the Structural Design chapter of the PPI Drainage Handbook for further explanation of the design methodology, design variables, and resulting factor of safety.

1. DESIGN EXAMPLE 1 – DEEP FILL OVER PP STORM DRAIN

Background

A contractor is installing a 36 in. diameter corrugated polypropylene (PP) storm drain in a trench with deep fill. The ground surface is at EL 18.42 ft, the groundwater table is at EL 9.71 ft, and the top of the pipe is at EL 3.42 ft. The local municipality requires a 75-year design life for the pipe. The site has no special live loading.

The pipe manufacturer has indicated that the pipe being installed has additional capacity beyond that indicated in the Maximum Burial Depth Table and can achieve the specified fill depth with clean, coarse-grained sand embedment material (Class II) compacted to 90% SPD rather than compacted crushed rock (Class I) material. The contractor has approached a design engineer to provide the final design.

Installation Parameters

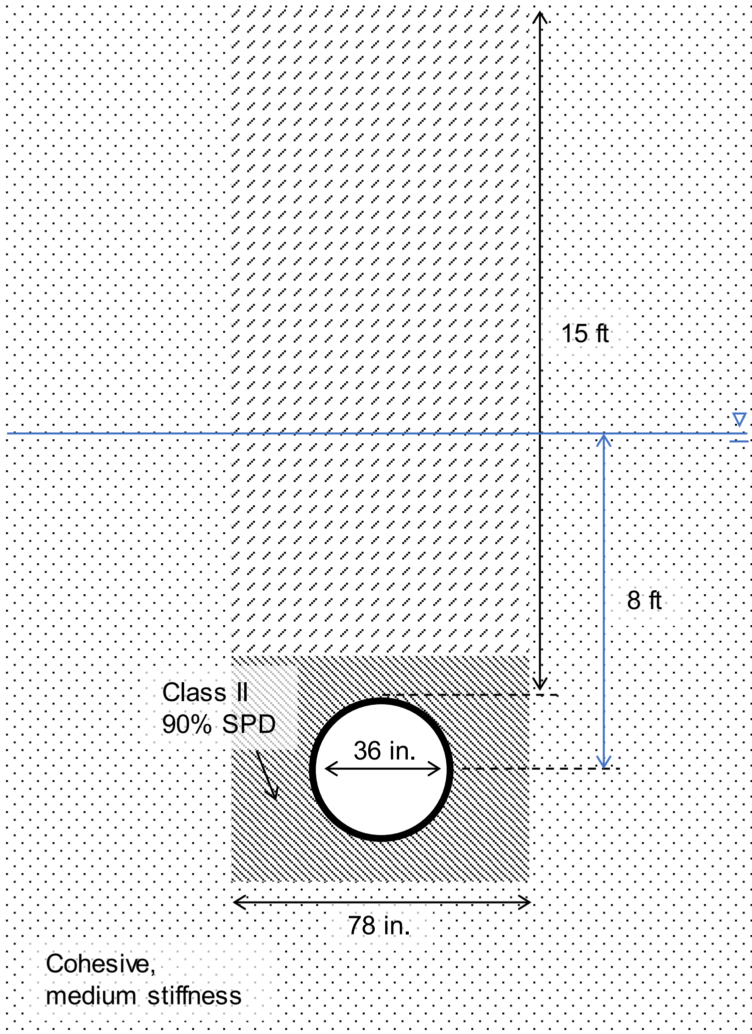
The site design drawings provide the following information.

Parameter	Value	Reference [1]
Embedment material	Class II 90% SPD	7.3.2, 7.3.3.1
Native soil	Cohesive, medium stiffness	7.3.3.2
Trench width, B_d	78 in. (6.5 ft)	
Fill depth, H	15 ft (EL 18.42 ft – EL 3.42 ft)	
Pipe inside diameter, D_i	36 in. (3 ft)	
Backfill soil moist unit weight, γ_s	120 pcf	7.4.1
Backfill soil saturated unit weight, γ_{sat}	136 pcf	7.4.1
Live load	Typical roadway (HL-93)	7.4.3
Design life	75 years	
Height of water table, H_w	8 ft above springline	

[1] All references are to relevant sections of the PPI Drainage Handbook

The manufacturer has provided to following additional information

Parameter	Value	Reference [1]
Pipe outside diameter, D_o	41 in. (3.42 ft)	7.2.3
Pipe centroid diameter, D	38.5 in.	7.2.3
Pipe wall gross area, A_g	0.65 in^2/in.	7.2.3
Pipe wall effective area, A_{eff}	0.54 in^2/in.	7.2.3.3, App C
Pipe moment of inertia, I_p	1.52 in^4/in.	7.2.3
Pipe stiffness	40 psi	7.2.2.1



[1] See Chapter 9 of the PPI Drainage Handbook for typical installation details

Design Steps

1. Loading - calculate loading on pipe (soil, hydrostatic, live).

2. Hoop thrust - calculate composite constrained modulus, vertical arching factor, and factored thrust strain. Check service stress and thrust strain limit.

3. Thrust plus bending - calculate pipe stiffness, shape factor, and service thrust strain. Calculate factored flexural strain in pipe, combine with factored thrust strain and check against permissible limits.

4. Deflection – calculate service deflection and check against allowable limit.

5. Global buckling – calculate global buckling strain capacity and compare to maximum thrust strain in pipe.

6. Flexibility factor – calculate the flexibility of the pipe and compare to specified limits.

7. Buoyancy – check for flotation of the pipe due to groundwater.

1.1 Loading

The dead load, or vertical soil prism pressure, is calculated as described in Section 7.4.1.

$\gamma_b = buoyant\ unit\ weight\ of\ soil$

$\gamma_b = \gamma_{sat} - \gamma_w$ (*Eq. 7-8*)

$\gamma_b = 136pcf - 62.4pcf$

$\gamma_b = 74pcf$

$P_{sp} = vertical\ soil\ prism\ pressure$ *at springline of pipe*

$P_{sp} = [H - (H_w - 0.5D_o)]\gamma_s + (H_w - 0.5D_o + 0.11D_o)\gamma_b$ (*Eq. 7-10*)

$P_{sp} = [15ft - (8ft - 0.5 * 3.42ft)] * 120pcf + (8ft - 0.5 * 3.42ft + 0.11 * 3.42ft) * 74pcf$

$P_{sp} = 1536psf = 10.7psi$

The hydrostatic load is calculated as described in Section 7.4.2. The factor for uncertainty in the level of the groundwater table, K_w is considered to be 1.3.

$P_w = hydrostatic\ groundwater\ pressure\ at\ springline\ of\ pipe$

$P_w = \gamma_w K_w H_w \leq \gamma_w(H + \frac{D_o}{2})$ (*Eq. 7-12*)

$P_w = 62.4pcf * 1.3 * 8ft$

$P_w = 649psf = 4.5psi$

Since the pipe is subject to HL-93 loads only and the fill depth is greater than 8 ft, live load can be neglected as described in Section 7.4.3.2.4. Special loads of greater magnitude, such as railroad, plane, or large crane loading, would still require consideration at this depth.

1.2 Hoop thrust

Per Table 7.3-2, the constrained modulus for Class II 90% SPD embedment material is 1,625 psi under a prism pressure of 10 psi and 1,800 psi under a prism pressure of 20 psi. Interpolate to determine the appropriate constrained modulus for the embedment material.

$M_{sb} = constrained\ modulus\ of\ embedment\ material$

$$M_{sb} = \frac{1800psi - 1625psi}{20psi - 10psi} * (10.7psi - 10psi) + 1625psi$$

$M_{sb} = 1637psi$

Since the trench width (B_d = 6.5 ft) is less than three times the pipe outside diameter ($3D_o$ = 10.3 ft), the effect of the adjacent native material should be considered. Per Table 7.3-5, a constrained modulus of 1,500 psi is appropriate for the medium stiffness cohesive native soil (M_{sn}). Interpolate from Table 7.3-6 to determine the soil support combining factor (S_c).

$^{B_d}/_{D_o} = {}^{78in}/_{41in} = 1.9$

$^{M_{sn}}/_{M_{sb}} = {}^{1500psi}/_{1637psi} = 0.92$

		B_d/D_o		
		1.75	**1.9**	**2.0**
M_{sn}/M_{sb}	**0.8**	0.9	0.918	0.93
	0.92		0.967	
	1	1	1	1

$S_c = 0.967$

$M_s = composite\ constrained\ modulus$

$M_s = S_c M_{sb}$ (*Eq. 7-7*)

$M_s = 0.967 * 1637psi$

$M_s = 1583psi$

Per Table 7.2-1, the long-term creep modulus of the pipe PP material (E_{lt}) for the 75-year design life is 28 ksi. The hoop stiffness factor (S_H) and vertical arching factor (VAF) are calculated as described in Section 7.5.2.3.1.

$$S_H = \frac{\phi_s M_s R}{E_{lt} A_g}$$ (*Eq. 7-23*)

$$S_H = \frac{0.9 * 1583psi * (0.5 * 38.5in)}{28000psi * 0.65\ {}^{in^2}/_{in}}$$

$S_H = 1.51$

$$VAF = 0.76 - 0.71\left[\frac{S_H - 1.17}{S_H + 2.92}\right]$$ (*Eq. 7-24*)

$$VAF = 0.76 - 0.71\left[\frac{1.51 - 1.17}{1.51 + 2.92}\right]$$

$$VAF = 0.70$$

The factored thrust at the pipe springline is calculated as described in Section 7.5.2.3.2. The maximum Strength I Limit State Load Factor for vertical earth load (γ_{EV}) from Table 7.5.1 is considered.

$$T_D = factored\ dead\ and\ hydrostatic\ thrust\ force$$

$$T_D = \eta_{EV}\left(\gamma_{EV}K_2(VAF)P_{sp} + \gamma_{WA}P_w\right)\frac{D_o}{2}$$ (*Eq. 7-25*)

$$T_D = 1.05(1.95 * 1.0 * 0.70 * 10.7psi + 1.0 * 4.5psi)\frac{41in}{2}$$

$$T_D = 410lbf/in$$

The maximum factored hoop thrust strain is calculated as described in Section 7.5.2.3.4.

$$\varepsilon_c = factored\ thrust\ strain$$

$$\varepsilon_c = \frac{T_D}{A_{eff}E_{lt}}$$ (*Eq. 7-30*)

$$\varepsilon_c = \frac{410lbf/in}{0.54\,{}^{in^2}/_{in} * 28000psi}$$

$$\varepsilon_c = 0.027 = 2.7\%$$

The maximum factored hoop thrust strain is checked against the limit as described in Section 7.5.2.3.5. The resistance factor (ϕ_t) is taken from Table 7.5-2. The compression strain limit (ε_{yc}) is taken from Table 7.2-3 for PP.

$$\varepsilon_c \le \phi_t\varepsilon_{yc}$$ (*Eq. 7-31*)

$$2.7\% \le 1.0 * 3.7\%$$

1.3 Thrust plus bending

Per Table 7.5-3, the shape factor for Class II embedment at 90% SPD (gravel – moderate compaction) is 3.5 for a pipe stiffness of 36 psi and 2.8 for a pipe stiffness of 72 psi. Interpolate to determine the appropriate shape factor for use in design of a pipe with 40 psi pipe stiffness.

$D_f = shape\ factor$

$D_f = \frac{2.8 - 3.5}{72psi - 36psi} * (40psi - 36psi) + 3.5$

$D_f = 3.42$

The service pipe thrust at the springline is calculated as described in Section 7.5.2.3.3 with all load factors excluded.

$T_{SD} = service\ thrust\ force$

$T_{SD} = \left(K_2(VAF)P_{sp} + P_w\right)\frac{D_o}{2}$

$T_{SD} = (1.0 * 0.70 * 10.7psi + 4.5psi)\frac{41in}{2}$

$T_{SD} = 245lbf/in$

The service hoop thrust strain is calculated as described in Section 7.5.2.3.4 using the gross section area.

$\varepsilon_{SC} = service\ thrust\ strain$

$\varepsilon_{SC} = \frac{T_{SD}}{A_g E_{lt}}$

$\varepsilon_{SC} = \frac{245lbf/in}{0.65\, {in^2}/{in} * 28000psi}$

$\varepsilon_{SC} = 0.013 = 1.3\%$

The centroid distance (c) is calculated from the inside, outside, and centroid diameters.

$c = \max\left(\frac{D_o - D}{2}, \frac{D - D_i}{2}\right) = \max\left(\frac{41in - 38.5in}{2}, \frac{38.5in - 36in}{2}\right) = 1.25in$

The flexural strain demand is calculated as described in Section 7.5.2.4.2.

$\varepsilon_f = factored\ flexural\ strain$

$\varepsilon_f = \gamma_{EV} D_f \frac{c}{R}\left(\frac{\delta D_i - \varepsilon_{SC} D}{D}\right)$ (*Eq. 7-32*)

$$\varepsilon_f = 1.95 * 3.42 * \frac{1.25in}{19.25in}\left(\frac{5\% * 36in - 1.3\% * 38.5in}{38.5in}\right)$$

$$\varepsilon_f = 0.015 = 1.5\%$$

The flexural and hoop thrust strains are combined and checked against the compression limit for combined thrust and bending as described in Section 7.5.2.4.4.

$$\varepsilon_f + \varepsilon_c \leq \phi_t 1.5\varepsilon_{yc} \qquad (Eq.\ 7\text{-}34)$$

$$1.5\% + 2.7\% \leq 1.0 * 1.5 * 3.7\%$$

$$4.2\% \leq 5.6\%$$

Since the hoop thrust strain, in compression, is greater than the flexural strain, the full section remains in compression and the net tension check described in Section 7.5.2.4.3 is not applicable.

1.4 Deflection

The pipe deflection under service loads is checked as described in Section 7.5.1.

$$\Delta_t = pipe\ deflection$$

$$\Delta_t = \frac{K_B D_L P_{sp} D_o}{\frac{E_{lt} I_p}{R^3} + 0.061 M_s} + \frac{K_B C_L P_L D_o}{\frac{E_{st} I_p}{R^3} + 0.061 M_s} + 2R\varepsilon_{sc} \qquad (Eq.\ 7\text{-}21)$$

$$\Delta_t = \frac{0.1 * 1.5 * 10.7psi * 41in}{\frac{28000psi * 1.52\,{in^4}/{in}}{(19.25in)^3} + 0.061 * 1583psi} + 2 * 19.25in * 1.6\%$$

$$\Delta_t = 1.27in$$

$$\Delta_t \leq \delta D_i \qquad (Eq.\ 7\text{-}22)$$

$$1.27in \leq 5\% * 36in$$

$$1.27in \leq 1.80in$$

1.5 Global buckling

Global buckling is checked as described in Section 7.5.2.5. The resistance factor (ϕ_{bck}) is taken from Table 7.5-2.

$$R_h = correction\ factor\ for\ backfill\ soil\ geometry$$

$$R_h = \frac{11.4}{11 + {}^{D}/_{12H}} \quad (Eq.\ 7\text{-}36)$$

$$R_h = \frac{11.4}{11 + {}^{38.5in}/_{12*15ft}}$$

$$R_h = 1.02$$

$$\varepsilon_{bck} = nominal\ global\ buckling\ strain\ resistance$$

$$\varepsilon_{bck} = \frac{1.2C_n\left(E_{lt}I_p\right)^{\frac{1}{3}}}{A_{eff}E_{lt}}\left[\frac{\phi_s M_s(1-2\nu)}{(1-\nu)^2}\right]^{\frac{2}{3}} R_h \quad (Eq.\ 7\text{-}35)$$

$$\varepsilon_{bck} = \frac{1.2*0.55*\left(28000psi*1.52\,{}^{in^4}/_{in}\right)^{\frac{1}{3}}}{0.54\,{}^{in^2}/_{in}*28000psi}\left[\frac{0.9*1583psi*(1-2*0.3)}{(1-0.3)^2}\right]^{\frac{2}{3}} *1.02$$

$$\varepsilon_{bck} = 0.17 = 17\%$$

$$\varepsilon_c \le \phi_{bck}\varepsilon_{bck} \quad (Eq.\ 7\text{-}37)$$

$$2.7\% \le 0.7*17\%$$

$$2.7\% \le 12\%$$

1.6 Flexibility factor

The flexibility factor is checked as described in Section 7.5.2.6. Per Table 7.2-1, the short-term creep modulus of the pipe PP material (E_{st}) is 175 ksi.

$$FF = flexibility\ factor$$

$$FF = \frac{D^2}{E_{st}I_p} \le 0.095\,in/lbf \quad (Eq.\ 7\text{-}38)$$

$$FF = \frac{(38.5in)^2}{175000psi*1.52\,{}^{in^4}/_{in}}$$

$$FF = 0.006in/lbf \le 0.095\,in/lbf$$

1.7 Buoyancy

The buoyant force is checked as described in Section 7.5.2.7. The Strength I Limit State Load Factor for hydrostatic load (γ_{WA}) and minimum for vertical earth load (γ_{EVmin}) are from Table 7.5.1. The resistance factor (ϕ_b) is taken from Table 7.5-2.

$F_{bd} = buoyant\ force\ demand$

$$F_{bd} = \frac{\pi}{4} {D_o}^2 \gamma_w \qquad (Eq.\ 7\text{-}39)$$

$$F_{bd} = \frac{\pi}{4} (3.42ft)^2 * 62.4pcf$$

$$F_{bd} = 572lbf/ft$$

$F_{br} = buoyant\ force\ resistance$

$$F_{br} = P_{sp} D_o \qquad (Eq.\ 7\text{-}40)$$

$$F_{br} = 1536psf * 3.42ft$$

$$F_{br} = 5247lbf/ft$$

$$\gamma_{WA} F_{bd} \leq \gamma_{EVmin} \phi_b F_{br} \qquad (Eq.\ 7\text{-}41)$$

$$1.0 * 572lbf/ft \leq 0.9 * 0.75 * 5247lbf/ft$$

$$572lbf/ft \leq 3542lbf/ft$$

Conclusion

The specified 36 in. diameter pipe with Class II embedment material compacted to 90% SPD is acceptable under 15 ft fill with water table 8 ft over the springline as it meets all strength and service limit states. The fill depth could be increased to 21 ft before the first limit state is exceeded (thrust strain).

Limit State	**Demand-to-Capacity Ratio (DCR)**	
	15 ft fill height (calculations shown)	**21 ft fill height**
Thrust strain	2.7% / 3.7% = 0.73	1.0
Thrust plus bending	4.2% / 5.6% = 0.75	0.86
Deflection	1.27 in. / 1.80 in. = 0.70	0.97
Global buckling	2.7% / 12.0% = 0.23	0.31
Flexibility factor	0.006 in/lbf / 0.095 in/lbf = 0.06	0.06
Buoyancy	572 lbf/ft / 3542 lbf/ft = 0.16	0.11

2. DESIGN EXAMPLE 2 – SHALLOW FILL OVER HDPE CULVERT

Background

An owner is developing a new building on her property. A 48 in. diameter HDPE culvert will be buried beneath the construction vehicle access path. The ground surface will be at EL +6.00 ft and the top of the pipe will be at EL +4.00 ft. Construction documents show a very narrow trench installation (1.5 times the pipe OD) with embedment material specified as limestone with max particle size of ¾ in. (gravel, dumped Class I). The owner has asked an engineer to determine whether the planned culvert installation will be able to withstand the construction vehicle loading. The construction vehicle is specified as having a maximum duration of 24 hours, with one 10 kip (1 kip = 1000 lb) front axle and two 45 kip rear axles.

Installation Parameters

The original construction documents provide the following information.

Parameter	Value	Reference
Embedment material	Dumped Class I (limestone)	7.3.2, 7.3.3.1
Native soil	Medium, cohesive material	7.3.3.2
Trench width, B_d	81 in. (6.5 ft, 1.5*OD)	
Fill depth, H	2 ft (EL 6 ft – EL 4 ft)	7.4.1, 7.5.6.1
Pipe inside diameter, D_i	48 in. (4 ft)	
Soil moist unit weight, γ_s	120 pcf	7.4.1
Height of water table, H_w	Below springline	

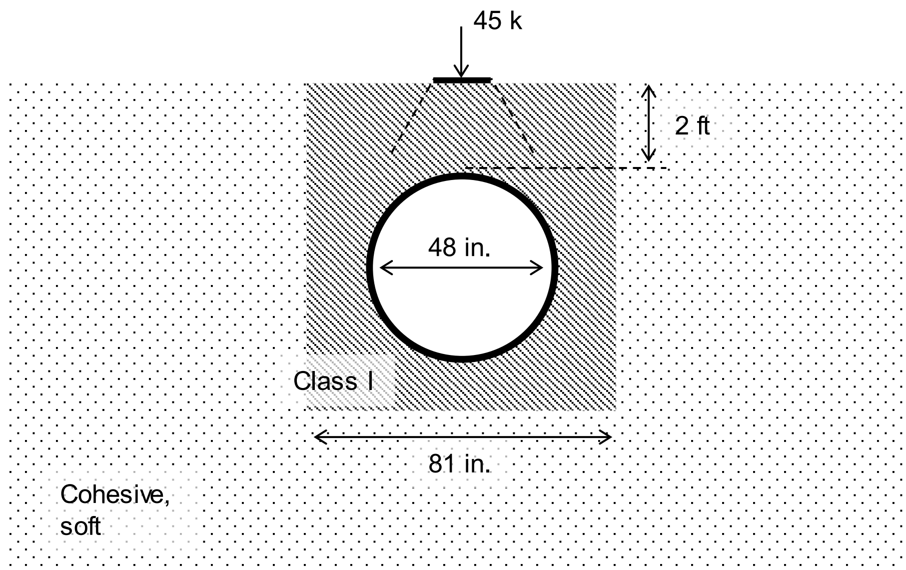
[1] All references are to relevant sections of the PPI Drainage Handbook

Manufacturer submittals for the specified pipe provide the following information.

Parameter	Value	Reference
Pipe outside diameter, D_o	54 in. (4.5 ft)	7.2.3
Pipe centroid diameter, D	50 in.	7.2.3
Pipe gross area, A_g	0.47 in^2/in.	7.2.3
Stub compression capacity, P_{st}	1200 lbf/in.	7.2.2.2
Pipe moment of inertia, I_p	0.54 in^4/in.	7.2.3
Project-specific HDPE material creep modulus for 24 hrs, E_{PE24}	50 ksi	

The owner has provided the following information.

Parameter	Value	Reference
Live load	Construction Vehicle 45 kip wheel load on 18 in. x 18 in. ground contact area	7.4.3.9
Design life	75 years	



[1] See Chapter 9 of the PPI Drainage Handbook for typical installation details

Design Steps

1. Loading - calculate loading on pipe (soil, hydrostatic, live).

2. Hoop thrust - calculate composite constrained modulus, vertical arching factor, and factored thrust strain. Check service stress and thrust strain limit.

3. Thrust plus bending - calculate pipe stiffness, shape factor, and service thrust strain. Calculate factored flexural strain in pipe, combine with factored thrust strain and check against permissible limits.

4. Deflection – calculate service deflection and check against allowable limit.

5. Global buckling – calculate global buckling strain capacity and compare to maximum thrust strain in pipe.

6. Flexibility factor – calculate the flexibility of the pipe and compare to specified limits.

7. Buoyancy – not applicable, water table below pipe.

2.1 Loading

The dead load, or vertical soil prism pressure, is calculated as described in Section 7.4.1.

$P_{sp} = vertical\ soil\ prism\ pressure\ at\ springline\ of\ pipe$

$P_{sp} = (H + 0.11D_o)\gamma_s$ for $H_w \leq 0.5D_o$, (*Eq. 7-9*)

$P_{sp} = (2ft + 0.11 * 4.5ft) * 120pcf$

$P_{sp} = 299psf = 2.1psi$

There is no hydrostatic load since the water table is below the springline.

This example will evaluate the construction vehicle wheel load with the specified maximum 24-hour duration. As stated in Section 7.4.3.9, construction live loads may be evaluated using a similar application method as that shown for the Design Truck in Section 7.4.3.1.1, considering the load magnitudes and ground surface contact areas specified by the municipality. For sustained loading, the dynamic load allowance (IM) is set to 1.0. .

The wheel load pressure is distributed through the soil as described in Section 7.4.3.2.3. Due to large axle spacing (8 ft) and shallow cover (2 ft), there is no interaction between the wheel loads (Eq. 7-14 and 7-15). The live load distribution factor (LLDF) for buried thermoplastic pipes with minimum fill depth is 1.15, as described in Section 7.4.3.2.3.

$l_d = distributed\ length\ of\ live\ load\ pressure\ at\ top\ of\ pipe$

$l_d = l_t + LLDF * H$ (*Eq. 7-16*)

$l_d = 18in + 1.15 * 24in$

$l_d = 45.6in$

$w_d = distributed\ width\ of\ live\ load\ pressure\ at\ top\ of\ pipe$

$w_d = w_t + LLDF * H + 0.06D_i$ (*Eq. 7-17*)

$w_d = 18in + 1.15 * 24in + 0.06 * 48in$

$w_d = 48.5in$

$P_L = vertical\ pressure\ at\ top\ of\ pipe\ due\ to\ live\ load$ (*Eq. 7-20*)

$$P_L = \frac{P_{surf}}{w_d l_d}$$

$$P_L = \frac{45000lbf}{45.6in * 48.5in}$$

$P_L = 20.3psi = 2930psf$

2.2 Hoop thrust

Per Table 7.3-1, the constrained modulus for Class I dumped limestone embedment material (M_{sb}) is 3,500 psi.

Typically for shallow installations (under 10 ft in cover depth) and stable trench walls, only the constrained soil modulus for embedment (M_{sb}) would be considered for design. Since unstable trench walls were encountered during installation, and the trench width (B_d = 6.75 ft) is less than three times the pipe outside diameter ($3D_o$ = 13.5 ft), the effect of the adjacent native material should be considered. Per Table 7.3-5, a constrained modulus of 1,500 psi is appropriate for the medium native soil (M_{sn}). Use Table 7.3-6 to determine the soil support combining factor (S_c).

$$B_d/D_o = 81in/54in = 1.5$$

$$M_{sn}/M_{sb} = 1500psi/3500psi = 0.43$$

$$S_c = 0.53$$

$$M_s = S_c M_{sb} \qquad (Eq.\ 7\text{-}7)$$

$$M_s = 0.53 * 3500psi$$

$$M_s = 1850psi$$

Per Table 7.2-1, the long-term creep modulus of the pipe HDPE material (E_{lt}) for the 75-year design life is 21 ksi and. the short-term modulus (E_{st}) is 110 ksi. The project specific 24-hr creep modulus (E_{PE24}) for the HDPE material is 50 ksi, as provided by the manufacturer. The hoop stiffness factor (S_H) and vertical arching factor (VAF) are calculated as described in Section 7.5.2.3.1.

$$S_H = \frac{\phi_s M_s R}{E_{lt} A_g} \qquad (Eq.\ 7\text{-}23)$$

$$S_H = \frac{0.9 * 1850psi * (0.5 * 50in)}{21000psi * 0.47\,in^2/in}$$

$$S_H = 7.98$$

$$VAF = 0.76 - 0.71\left[\frac{S_H - 1.17}{S_H + 2.92}\right] \quad (Eq.\ 7\text{-}24)$$

$$VAF = 0.76 - 0.71\left[\frac{7.98 - 1.17}{27.98 + 2.92}\right]$$

$$VAF = 0.32$$

The corrugation effective area (A_{eff}) is calculated based on stub compression test results, as described in Section 7.2.3.4.5. The time factor (K_t) is taken from Table 7.2-4. The yield strength (F_y) is taken from Table 7.2-2.

$$A_{eff} = \frac{P_{st}K_t}{F_y} \leq A_g \quad (Eq.\ 7\text{-}2)$$

$$A_{eff} = \frac{1200lbf/in * 0.25}{900psi}$$

$$A_{eff} = 0.33\,{}^{in^2}\!/_{in}$$

The factored thrust at the pipe springline is calculated as described in Section 7.5.2.3.2. The construction vehicle is treated as an owner-specified load with reduced live load factor as described in Section 7.5.4.

$$T_D = factored\ long\ term\ dead\ and\ hydrostatic\ thrust\ force$$

$$T_D = \eta_{EV}\left(\gamma_{EV}K_2(VAF)P_{sp}\right)\frac{D_o}{2} \quad (Eq.\ 7\text{-}25)$$

$$T_D = 1.05(1.95 * 1.0 * 0.32 * 2.1psi)\frac{54in}{2}$$

$$T_D = 36lbf/in$$

$$F_1 = live\ load\ distribution\ adjustment\ factor$$

$$F_1 = \max\left(\frac{0.75D_o}{l_d}, \frac{15}{D_i}, 1.0\right) \quad (Eq.\ 7\text{-}27)$$

$$F_1 = \max\left(\frac{0.75 * 54in}{45.6in}, \frac{15}{48in}, 1.0\right) = \max(0.89, 0.31, 1.0) = 1$$

$$F_2 = soil\ type\ live\ load\ thrust\ correction\ factor$$

$$F_2 = \frac{0.95}{1 + 0.6S_H} \quad (Eq.\ 7\text{-}28)$$

$$F_2 = \frac{0.95}{1 + 0.6 * 7.98} = 0.16$$

$$C_L = live\ load\ coefficient$$

$$C_L = {}^{l_d}/_{D_o}$$

$$C_L = {}^{45.6in}/_{54in} = 0.84$$

$$T_L = factored\ live\ load\ thrust\ force$$

$$T_L = \eta_{LL}\gamma_{LL}C_L F_1 F_2 P_L \frac{D_o}{2}$$ (*Eq. 7-26*)

$$T_L = 1.0 * 1.35 * 0.84 * 1.0 * 0.16 * 20.3psi\frac{54in}{2}$$

$$T_L = 103lbf/in$$

The maximum factored hoop thrust strain is calculated as described in Section 7.5.2.3.4.

$$\varepsilon_c = factored\ thrust\ strain$$

$$\varepsilon_c = \frac{T_D}{A_{eff}E_{lt}} + \frac{T_L}{A_{eff}E_{PE24}}$$ (*Eq. 7-30*)

$$\varepsilon_c = \frac{36lbf/in}{0.33\,{}^{in^2}/_{in} * 21000psi} + \frac{103lbf/in}{0.33\,{}^{in^2}/_{in} * 50000psi}$$

$$\varepsilon_c = 0.011 = 1.1\%$$

The maximum factored hoop thrust strain is checked against the limit as described in Section 7.5.2.3.5. The resistance factor (ϕ_t) is taken from Table 7.5-2. The compression strain limit (ε_{yc}) is taken from Table 7.2-3 for HDPE.

$$\varepsilon_c \leq \phi_t\varepsilon_{yc}$$ (*Eq. 7-31*)

$$1.1\% \leq 1.0 * 4.1\%$$

2.3 Thrust plus bending

Since the pipe stiffness (PS) is not provided, it is calculated as described in Section 7.2.2.1.

$$PS = \frac{E_{st}I_p}{0.149R^3}$$ (*Eq. 7-1*)

$$PS = \frac{110000\text{psi} * 0.54\,{}^{in^4}/_{in}}{0.149 * (0.5 * 50in)^3}$$

$PS = 25.5\text{psi}$

Per Table 7.5-3, the shape factor for dumped Class I embedment (gravel - dumped) is 3.5 for a pipe stiffness of 18 psi and 2.8 for a pipe stiffness of 36 psi. Interpolate to determine the appropriate shape factor for use in design of a pipe with 25.5 psi pipe stiffness.

$D_f = shape\ factor$

$D_f = \frac{2.8 - 3.5}{36psi - 18psi} * (25.5psi - 18psi) + 3.5$

$D_f = 3.21$

The service pipe thrust at the springline is calculated as described in Section 7.5.2.3.2 with all load factors excluded.

$T_{SD} = service\ long\ term\ dead\ and\ hydrostatic\ thrust\ force\ at\ the\ springline$

$T_{SD} = \left(K_2(VAF)P_{sp} + P_w\right)\frac{D_o}{2}$

$T_{SD} = (1.0 * 0.32 * 2.1psi)\frac{54in}{2}$

$T_{SD} = 18lbf/in$

$T_{SL} = service\ live\ load\ thrust\ force$

$T_{SL} = C_L F_1 F_2 P_L \frac{D_o}{2}$

$T_{SL} = 0.84 * 1.0 * 0.16 * 20.3psi\frac{54in}{2}$

$T_{SL} = 76lbf/in$

The service hoop thrust strain is calculated as described in Section 7.5.2.3.4 using the gross section area.

$\varepsilon_{SC} = service\ thrust\ strain$

$$\varepsilon_{SC} = \frac{T_{SD}}{A_g E_{lt}} + \frac{T_{SL}}{A_g E_{PE24}} \qquad \textit{(Eq. 7-30)}$$

$$\varepsilon_{SC} = \frac{18lbf/in}{0.47\ {in^2}/{in} * 21000psi} + \frac{76lbf/in}{0.47\ {in^2}/{in} * 50000psi}$$

$\varepsilon_{SC} = 0.005 = 0.5\%$

The centroid distance (c) is calculated from the inside, outside, and centroid diameters.

$$c = \max\left(\frac{D_o - D}{2}, \frac{D - D_i}{2}\right) = \max\left(\frac{54in - 50in}{2}, \frac{50in - 48in}{2}\right) = 2in$$

The flexural strain demand is calculated as described in Section 7.5.2.4.2.

$\varepsilon_f = factored\ flexural\ strain$

$$\varepsilon_f = \gamma_{EV} D_f \frac{c}{R}\left(\frac{\delta D_i - \varepsilon_{SC} D}{D}\right) \qquad (Eq.\ 7\text{-}32)$$

$$\varepsilon_f = 1.95 * 3.21 * \frac{2in}{0.5 * 50in}\left(\frac{5\% * 48in - 0.5\% * 50in}{50in}\right)$$

$$\varepsilon_f = 0.022 = 2.2\%$$

The flexural and hoop thrust strains are combined and checked against the compression limit for combined thrust and bending as described in Section 7.5.2.4.4.

$$\varepsilon_f + \varepsilon_c \leq \phi_t 1.5 \varepsilon_{yc} \qquad (Eq.\ 7\text{-}34)$$

$$2.2\% + 1.1\% \leq 1.0 * 1.5 * 4.1\%$$

$$3.3\% \leq 6.1\%$$

To check net tension strain, as described in Section 7.5.2.4.3, the minimum thrust strain is calculated using the minimum dead load factor and the reduction factor for thrust at the crown ($K_2 = 0.6$).

$$T_D = \eta_{EV}\left(\gamma_{EV} K_2 (VAF) P_{sp}\right)\tfrac{D_o}{2}, \qquad (Eq.\ 7\text{-}25)$$

$$T_D = 1.0(0.9 * 0.6 * 0.32 * 2.1psi)\frac{54in}{2}$$

$$T_D = 22lbf/in$$

$$\varepsilon_c = \frac{22lbf/in}{21000psi * 0.33\, {in^2}/{in}} + \frac{103lbf/in}{50000psi * 0.33\, {in^2}/{in}} \qquad (Eq.\ 7\text{-}30)$$

$$\varepsilon_c = 0.9\%$$

The hoop thrust strain is checked against the limit as described in Section 7.5.2.4.3. The resistance factor for flexure (ϕ_f) is taken from Table 7.5-2. The compression strain limit (ε_{yt}) is taken from Table 7.2-3 for HDPE.

$$\left|\varepsilon_f - \varepsilon_c\right| \leq \phi_f \varepsilon_{yt} \qquad (Eq.\ 7\text{-}33)$$

$$|2.2\% - 1.1\%| \leq 1.0 * 5.0\%$$

$$1.1\% \leq 5.0\%$$

Since the flexural strain is less than the minimum thrust strain, net tension will not occur for the mid-term loading. Note that net tension will occur for short-term loading of the wheel load (but is less than the limit).

2.4 Deflection

The pipe deflection under service loads is checked as described in Section 7.5.1.

$$\Delta_t = pipe\ deflection$$

$$\Delta_t = \frac{K_B D_L P_{sp} D_o}{\frac{E_{lt} I_p}{R^3} + 0.061 M_s} + \frac{K_B C_L P_L D_o}{\frac{E_{PE24} I_p}{R^3} + 0.061 M_s} + 2R\varepsilon_{sc} \qquad (Eq.\ 7\text{-}21)$$

$$\Delta_t = \frac{0.1 * 1.5 * 2.1psi * 54in}{\frac{21000psi * 0.54\, {in^4}/{in}}{(0.5 * 50in)^3} + 0.061 * 1850psi} + \frac{0.1 * 0.84 * 20.4psi * 54in}{\frac{50000psi * 0.54\, {in^4}/{in}}{(0.5 * 50in)^3} + 0.061 * 1850psi} + 2 * 0.5 * 50in * 0.7\%$$

$$\Delta_t = 0.15in + 0.81in + 0.36in$$

$$\Delta_t = 1.3in$$

$$\Delta_t \leq \delta D_i \qquad (Eq.\ 7\text{-}22)$$

$$1.3n \leq 5\% * 48in$$

$$1.3in < 2.4in$$

$$\frac{1.3in}{48in} = 2.7\% < 5\%$$

Deflection under sustained construction vehicle loading is expected to be less than the typical 5% limit.

2.5 Global buckling

Global buckling is checked as described in Section 7.5.2.5.

$R_h = correction\ factor\ for\ backfill\ soil\ geometry$

$$R_h = \frac{11.4}{11 + {}^{D}/_{12H}} \quad \text{(Eq. 7-36)}$$

$$R_h = \frac{11.4}{11 + {}^{50in}/_{12 * 2ft}}$$

$$R_h = 0.87$$

$v = Poisson\ Ratio$, estimated as 0.3 per Section 7.5.2.5

$\varepsilon_{bck} = nominal\ global\ buckling\ strain\ resistance$

$$\varepsilon_{bck} = \frac{1.2C_n\left(E_{lt}I_p\right)^{\frac{1}{3}}}{A_{eff}E_{lt}}\left[\frac{\phi_s M_s(1-2v)}{(1-v)^2}\right]^{\frac{2}{3}} R_h \quad \text{(Eq. 7-35)}$$

$$\varepsilon_{bck} = \frac{1.2 * 0.55 * \left(21000psi * 0.54\ {}^{in^4}/_{in}\right)^{\frac{1}{3}}}{0.33\ {}^{in^2}/_{in} * 21000psi}\left[\frac{0.9 * 1850psi * (1 - 2 * 0.3)}{(1-0.3)^2}\right]^{\frac{2}{3}} * 0.87$$

$$\varepsilon_{bck} = 0.23 = 23\%$$

$$\varepsilon_c \leq \phi_{bck}\varepsilon_{bck} \quad \text{(Eq. 7-37)}$$

$$1.1\% \leq 0.7 * 23\%$$

$$1.1\% \leq 15.9\%$$

2.6 Flexibility factor

The flexibility factor is checked as described in Section 7.5.2.6.

$FF = flexibility\ factor$

$$FF = \frac{D^2}{E_{st}I_p} \leq 0.095\ in/lbf \quad \text{(Eq. 7-38)}$$

$$FF = \frac{(50in)^2}{110000psi * 0.54\ {}^{in^4}/_{in}}$$

$$FF = 0.042in/lbf \leq 0.095\ in/lbf$$

2.7 Buoyancy

Since the maximum water table is below the pipe, buoyant force is not a concern.

Conclusion

The deflection of the specified 48 in. diameter HDPE pipe under the maximum construction vehicle wheel loading is expected to be 2.7%, less than the 5% limit.

Limit State	Demand-to-Capacity Ratio (DCR)
Thrust strain	1.1% / 4.1% = 0.28
Thrust plus bending	3.3% / 6.1% = 0.54
Deflection	2.7% / 5% = 0.55
Global buckling	1.1% / 15.9% = 0.07
Flexibility factor	0.042 in/lbf / 0.095 in/lbf = 0.44
Buoyancy	NA