11. Economics

11.1 Introduction to Engineering Economics

This section of the handbook describes some of the general economic principles and considerations that are associated with specifying corrugated plastic pipe (CPP) for drainage applications. It is worth noting that a complete economic analysis is difficult to perform since there are multiple fluctuating variables that directly affect the analysis. Some of these variables include geographical location, proximity to plants and distribution centers, types of native materials present, availability of structural backfill materials, fluctuating prices of raw materials used in manufacturing the pipes, pipe size, maintenance costs, and whether or not the bidding process allows for competition and alternative materials.

The following sections detail some of the factors to consider when conducting an economic analysis and provide some general guidelines for the various types of pipes used in drainage applications. An example of a life cycle cost analysis is illustrated in Section 11.3.

11.2 Cost Considerations for Engineering Economic Analysis

There are several considerations when assessing the overall cost of the pipe system evaluated in the economic analysis. While attempting to make an economic decision between two or more pipe materials for a given application, it may be tempting to simply compare the costs of each pipe material. However, this will likely lead to an erroneous conclusion, as there are many other factors that must be considered in the economic analysis. Beyond the pipe material costs, one has to consider the costs of installation and transportation. These are typically grouped together as "Installed Costs".

Additionally, one must consider the maintenance costs of the pipe system and the desired service life of the pipe system for the given application. If the anticipated service life of the pipe system is less than the desired life, the replacement costs must be considered in the overall life cycle cost analysis. This is discussed further in Section 11.3.

Finally, it is important to consider the impact of competition on the cost of installed pipe systems. As with any product, the presence of competition has the effect of reducing overall prices, particularly when there are multiple materials or products with equivalent performance for a given application from which to choose.

11.2.1 Material Costs

For the purposes of this handbook, two primary material costs will be considered that affect the overall cost of a pipe system: 1) the cost of the raw materials used in manufacturing the pipe; and, 2) the cost of the backfill materials used for installing the pipe. In reality, the product cost consists of much more than simply the cost of the raw materials, since a great deal of processing and tooling goes into the manufacturing of a pipe (see Chapter 3). However, since the cost of a given pipe system is directly related to the cost of the raw materials used in manufacturing the system, it is appropriate to limit the discussion of product costs in this handbook to the raw material costs.

Raw materials for pipe manufacturing

Corrugated HDPE pipes are manufactured from high density polyethylene resins (96 to 98%) and carbon black or other colorant (2 to 4%). Similarly, corrugated PP pipes are manufactured from polypropylene resins (95 to 98%) and other additives (2 to 5%). Chapter 3 provided a review of the manufacturing process for these pipes. The price of resin fluctuates based on supply and demand as well as other various factors. Unlike reinforced concrete pipe, which has several different ingredients (e.g., cement, aggregates, binders, additives, etc.) that affect its cost, both corrugated HDPE and PP are composed of one primary respective ingredient.

Corrugated HDPE pipes can be manufactured with post-consumer and post-industrial recycled materials, which typically cost less than virgin materials. However, the prices of the recycled materials will also fluctuate based on the supply and demand. Also, the manufacturing costs for pipes produced with recycled materials may be more than those for pipes manufactured with virgin materials, due to the costs of filtering and processing the materials.

Backfill materials for pipe installation

Since the performance of an installed pipe is largely dependent on the soil envelope around the pipe (as discussed in Chapter 7), the cost of the installed pipe system must take into account the cost of the backfill materials used in the pipe envelope. This is one of the greatest variables in the overall cost of the system, as different pipe types can require different kinds or volumes of backfill materials, and the availability of backfill materials can vary greatly by location. Generally speaking, flexible pipes such as corrugated HDPE and PP pipes require structural backfill material to be placed and compacted around the pipe up to a height of 6 in. (15 cm) above the pipe as presented in Chapter 9. Above this height, native excavated materials may be used. The cost of the structural backfill material varies depending on the type of material available as well as the proximity to the jobsite. The cost of backfill materials is typically included in the bid for the project.

11.2.2 Installation Costs

Corrugated HDPE and PP pipes are typically installed in open-cut trenches and backfilled with structural fill. Smaller diameter pipes can also be trenched in for agricultural applications. Regardless, the cost of the pipe system must take into account the cost to install the pipes. In general, the installation costs for corrugated HDPE and PP pipes are less than those for competitive materials such as reinforced concrete pipe and corrugated metal pipe. One of the reasons for this is that corrugated HDPE and PP pipes are manufactured in 20 ft (6 m) lengths, while rigid pipes such as reinforced concrete pipe are typically manufactured in 8 ft (2.5 m) lengths. Additionally, since the pipes are manufactured with in-line bells and spigots, it is not necessary to excavate bell holes which saves time during excavation. Finally, smaller diameter pipes are lightweight and can be handled and maneuvered without the use of large equipment which saves time and costs during installation. As with the backfill materials, the installation costs are typically included in the bid for the project.

11.2.3 Transportation Costs

The transportation costs include the cost to transport the pipe to the jobsite as well as the costs to transport the pipe from a manufacturing plant to a distributor, if necessary. Corrugated HDPE and PP pipes have at least two advantages over competitive materials in terms of transportation costs. First, since they weigh less than pipes made of competitive materials (e.g., corrugated metal pipe and reinforced concrete pipe), more pipe can be loaded per truck which results in fewer trips to deliver a given footage of pipe to a jobsite. Second, the corrugated HDPE and PP pipes are sized so that they can be nested, with smaller diameter pipes fitting inside larger diameter pipes. This allows for efficient packing on trucks and maximizes the footage of pipe that can be carried per load.

11.2.4 Maintenance Costs

The proper maintenance of pipes is necessary for ensuring their long-term performance and function as discussed in Chapter 10. Maintenance typically includes periodic cleaning via water jetting or vacuum, as well as inspections and repairs if needed. Smooth-lined CPP is very easy to clean due to the low coefficient of friction between any debris and the pipe wall. Additionally, since the number of joints is minimized due to the longer pipe lengths, there is typically less sediment build-up in CPP as compared with pipes made with other competitive materials.

11.2.5 Service Life and Replacement Costs

The desired service life of the pipe system must be considered when conducting an engineering economic analysis. Many state DOTs now require a 75 or 100 year service life for their culverts and storm drain systems.

Corrugated HDPE pipe, manufactured with virgin or recycled materials or both, has a service life of 100 years, as does corrugated PP pipe (as discussed in Chapter 3). If the service life of the pipe in the given conditions is less than that required by the owner, the replacement cost for the pipe must be taken into account in the life cycle cost analysis.

11.2.6 Effects of Competition and Alternative Materials

One of the biggest impacts on the overall cost of an installed pipe system is the presence (or lack thereof) of competing materials. The AASHTO has recognized the benefits of competition in drainage systems and funded a research project in 2015 to develop a performance-based process for the selection of drainage pipe materials, published in NCHRP Report 801 (1). As stated in the forward of the report,

> *"Traditionally, transportation agencies have used a "means and methods" approach for selection and specification of products such as drainage pipe systems. In this approach, the owner-agencies specify a particular drainage pipe system during the design process, and the cost of the specified system is included in the contractors' bids for the project. This research investigated an alternative approach, the use of a performance-based process for selection of drainage pipe systems. Such a selection process is based on satisfying performance criteria for the drainage system while considering the full range of suitable pipe materials. This approach has the potential to foster competition among various pipe types judged to be of satisfactory quality and equally acceptable on the basis of engineering and cost analyses. Giving contractors the ability to choose from among alternative drainage pipe systems during the bidding process on the basis of performance and cost can help agencies promote competition that will lower agency costs while achieving satisfactory performance." (1)*

The project resulted in a proposed methodology that allowed users to select drainage system materials from a pool of equivalent-performing products and showed that cost reductions due to competition are likely, if such a pool of equivalent materials exists. Furthermore, the cost reductions are realized even if the municipality uses the same material it would have used if open competition did not exist, simply due to the impact of competition.

The importance of competition in the bidding process was further demonstrated in a research study conducted for the American Chemistry Council by BCC Research in November 2016 (2). The research project included a comparison of installed pipe costs in several municipalities in Texas, some of which allow several alternative material choices for their stormwater drainage applications and some of which limit their drainage materials only to reinforced concrete pipe. The research project concluded that *"communities with open competition enjoy lower pipe cost, on average, for stormwater projects, reaching savings of up to 57% in comparison to municipalities employing closed competition practices"* (2). A graphical summary of the data is shown in Figure 11. 1 and a tabular summary of the cost savings is shown in Table 11. 1.

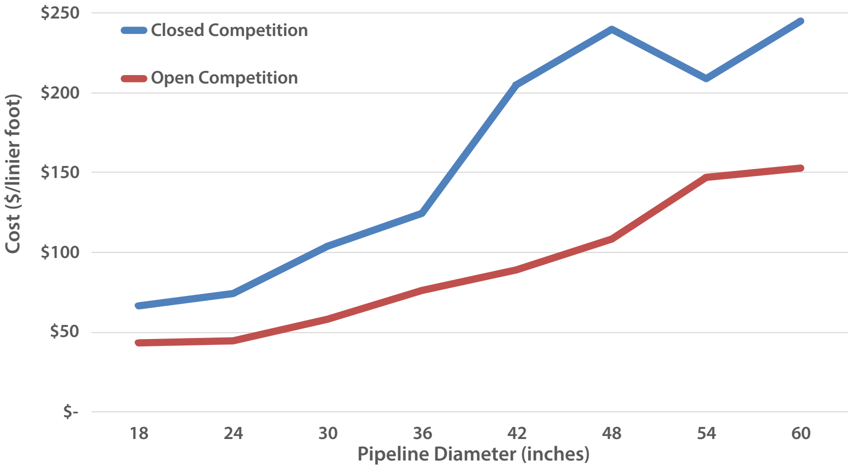

Figure 11.1: Summary of installed cost differences in various communities in Texas based on open vs. closed competition for drainage system materials (2)

Table 11. 1: Average cost for closed and open competition, and percent savings identified for open over closed competition for several municipalities in Texas (2)

Pipe diameter, in.(cm)	Closed Competition	Open Competition	Percent Savings from Open Competition
18 (45)	$66.64	$43.44	35%
24 (60)	$74.19	$44.63	40%
30 (76)	$103.66	$58.01	44%
36 (90)	$124.76	$75.93	39%
42 (106)	$205.41	$89.04	57%
48 (120)	$239.99	$108.60	55%
54 (137)	$209.11	$146.95	30%
60 (152)	$245.35	$152.80	38%

11.3 Life Cycle Cost Analysis

A life cycle cost analysis (LCCA) is important to compare the overall present value costs of various pipe materials. The LCCA considers more than just the material costs of the various pipe systems. It also includes the installation costs, the maintenance and repair costs, the replacement costs, and the anticipated service life as factors to include in the analysis. The LCCA considers the discount rate and converts all costs into present values to determine an accurate comparison of the various systems being evaluated.

There are many available methods currently used to calculate the life-cycle cost of various pipe products. The ASTM standard C1131, *Standard Practice for Least Cost (Life Cycle) Analysis of Concrete Culvert, Storm Sewer, and Sanitary Sewer Systems*, is often specified by the concrete pipe industry (3). The ASTM standard A930, *Practice for Life-Cycle Cost Analysis of Corrugated Metal Pipe Used for Culverts, Storm Sewers, and other Buried Conduits*, is referenced by the corrugated metal pipe industry (4). The analysis utilized in this handbook is based on the ASTM standard F1675, *Standard Practice for Life-Cycle Cost Analysis of Plastic Pipe Used for Culverts, Storm Sewers, and Other Buried Conduits* (5).

ASTM F1675 details a procedure to evaluate alternative pipe products with respect to their overall economic impact, given the service life of the pipe and the intended design service life of the application. For example, if the given application requires a design service life of 100 years, a product that lasts 50 years would require a replacement (and associated replacement costs) in order to meet the design requirement, while a 100 year product would not need to be replaced. Additionally, ASTM F1675 considers the maintenance and repair costs of each pipe system, as well as the residual value of the pipe systems. This is an important distinction for pipes that can be reused or recycled at the end of their intended service life.

To compute the life cycle costs for the various drainage systems, ASTM F1675 utilizes the following equation:

$$PVLCC = PVIC + PVM + PVR - PVT \qquad \text{(Eqn. 11. 1)}$$

where:

$PVLCC =$ present value life cycle cost;

$PVIC =$ present value of initial costs;

$PVM =$ present value of operating and maintenance costs;

$PVR =$ present value of replacement or rehabilitation costs; and,

$PVT =$ present value of terminal or residual Costs.

The *PVIC* is taken as simply the initial cost of the pipe system (including material and installation costs) and is not discounted, since this cost occurs at Year 0 in the analysis. The remaining costs used in the LCCA are discounted to determine their present value, given the year (or years) in which the expenditures occur and the intended design life of the pipe system. The following example illustrates how this methodology can be applied to pipe infrastructure.

11.3.1 Example Analysis – ASTM F1675 LCCA

In this example analysis, five pipe types are considered: 1) Class III Reinforced Concrete Pipe (RCP); 2) Galvanized Corrugated Metal Pipe (CMP); 3) Corrugated HDPE Pipe with Virgin Materials (HDPE Virgin); 4) Corrugated HDPE Pipe with PCR Materials (HDPE Recycled); and, 5) Corrugated PP Pipe. For the purposes of this analysis, all pipe types have an inside diameter of 24 in. (600 mm).

For this example, it is assumed that all pipe materials require the same backfill materials and have comparable trench widths, such that the pipe envelope materials are the same for all pipe types. This is an appropriate assumption that applies for many railway applications, although this is not always the case in highway and other drainage applications. For example, concrete pipe can often be installed with select backfill materials that are only compacted up to the springline of the pipe and native materials are used in the remainder of the backfill envelope (as presented in Chapter 9), while flexible pipes typically require select backfill materials to extend 6 in. (15 cm) above the top of the pipe. Also, depending on the hydraulic requirements of the culvert, it is likely that a larger diameter CMP pipe may be necessary to achieve the equivalent hydraulic capacities of the smooth-lined HDPE and RCP pipe systems. This would also necessitate a larger pipe envelope. However in this analysis, all pipe envelopes are assumed to be the same.

Because RCP, Corrugated HDPE, and Corrugated PP pipes all have a smooth inner surface, it is prudent to assume that the ongoing maintenance and cleaning costs of these pipes will be slightly less than those of the CMP. Additionally, since there are 60% fewer joints on the HDPE and PP pipe systems as compared with the RCP systems, the HDPE and PP pipe systems will have a slightly lower annual maintenance cost than RCP.

For this example, the desired design service life for the pipe system is assumed to be 100 years. RCP, HDPE (virgin and recycled), and PP pipes all have a material service life of 100 years, while the service life of galvanized CMP is typically around 50 years or less, depending on the installation conditions, type of soil, and type of effluent present. As such, the CMP system requires replacement prior to the end of the desired pipe system design life and this replacement cost must be considered in the LCCA.

The discount rate is used to convert future occurring costs to an equivalent cost at Time Year 0 (present). ASTM F1675 defines both a nominal discount rate and a real discount rate. The nominal discount rate includes the rate of general inflation over the study period, while the real discount rate represents the actual earning power of money over and above inflation. The two values are related as shown in Eqn. 11.2:

$$d_r = \frac{1+d_n}{1+I} \qquad \text{(Eqn. 11.2)}$$

where:

$d_r =$ real discount rate;

$d_n =$ nominal discount rate; and,

$I =$ the rate of general price inflation.

An inflation rate of 2% and a nominal discount rate of 3% are used in this example analysis, resulting in a real discount rate of 0.98%. These rates are based on historical averages over the past 20 years. The present value of a future cost occurring at a single point in time (e.g., the replacement cost of the pipe system) can be calculated by using Eqn. 11.3:

$$PVA_S = A_S * \left(\frac{1}{1+d_r}\right)^n \qquad \text{(Eqn. 11.3)}$$

where:

$PVA_S =$ present value of a single future expenditure;

$A_S =$ the amount of the future expenditure;

$d_r =$ real discount rate; and,

$n =$ number of years from Year 0 to the time of the future expenditure.

Similarly, the present value of future recurring costs expected to occur in the same amount at the same frequency (e.g., annual maintenance costs) are discounted into present value dollars according to Eqn. 11.4:

$$PVA_r = A_r * \frac{(1+d_r)^n - 1}{d_r(1+d_r)^n} \qquad \text{(Eqn. 11. 4)}$$

where:

$PVA_r =$ present value of future recurring expenditure;

$A_r =$ future recurring annual costs;

$d_r =$ real discount rate; and,

$n =$ number of years over which the recurring annual costs occur.

Using Equations 11.1 through 11. 4, in accordance with ASTM F1675, the present values of the various pipe systems can be calculated given their estimated initial costs and ongoing maintenance costs. While these costs can vary greatly depending on region, material availability, and other factors, the assumed costs for the 24 in. (60 cm) diameter pipes evaluated in this analysis are summarized in Table 11.2. These costs are based on the data provided from the BCC Research study (2) and estimates from various highway and railroad installations around the United States. The costs represent installed costs (including pipe materials, backfill materials, transportation, and installation costs) and assume trench installations, sandy gravel soils for the pipe envelope, and the reuse of excavated native soils for backfill above the pipe. Incorporating recycled materials into corrugated HDPE pipe has been shown to reduce the costs by 15 to 25%, depending on the fluctuations in resin prices (6). A reduction of 20% was used in this analysis.

Higher maintenance costs were assumed for CMP pipes than HDPE and RCP, due to their rough interior which may require more frequent or time-intensive cleaning. RCP maintenance costs may also be slightly higher than HDPE due to the increased number of joints. Because of this, operation and maintenance costs were assumed to be $0.50/ft/year ($1.64/m/year) for RCP, $0.75/ft/year ($2.46/m/year) for CMP, and $0.40/ft/year ($1.31/m/year) for Corrugated HDPE and PP. These costs included video inspections, cleaning, and general maintenance of the pipes. These costs represent estimates that may vary greatly by region and application. For ease of analysis, the terminal value was set to zero for all of the pipe products. However, in reality the Corrugated HDPE pipe could be recycled and therefore, some residual value would be assigned to it. Likewise, portions of the RCP and CMP products could potentially be salvaged and also have some residual value assigned to them.

Using these factors, the results are summarized in Table 11.2. Additionally, the cost per year for each pipe system, given the initial costs and expected service lives of each pipe material, was determined by creating a Microsoft® Excel spreadsheet and utilizing the PPMT function. This spreadsheet assumed a discount rate of 0.98% and provided the value of an annuity that yields the same present value of the current cost. Using the same assumptions described above, this cost is also included in Table 11.2.

Table 11.2: Life Cycle Cost Analysis in accordance with ASTM F1675 for various 24 in. (60 cm) diameter pipes based on typical average installed operating and maintenance costs

Pipe Type	Material Service Life (years)	Initial Installed Cost - $/ft ($/m)	Annual Op. and Maint. Cost - $/ft ($/m)	Replace. Cost - $/ft ($/m)	PV of Op. and Maint. - $/ft ($/m)	PV of Replace. Cost - $/ft ($/m)	Total PV - $/ft ($/m)	Cost per Year - $/ft ($/m)
RCP	100	75 (246)	0.50 (1.64)	0 (0)	32 (104)	0 (0)	106.78 (350.24)	1.66 (5.87)
CMP	50	50 (164)	0.75 (2.46)	50 (164)	48 (156)	31 (101)	128.36 (421.02)	3.23 (10.47)
HDPE Virgin	100	45 (148)	0.40 (1.31)	0 (0)	25 (83)	0 (0)	70.42 (230.98)	1.10 (3.87)
HDPE Recycled	100	40 (131)	0.40 (1.31)	0 (0)	25 (83)	0 (0)	65.42 (214.58)	1.02 (3.35)
PP	100	50 (164)	0.40 (1.31)	0 (0)	25 (83)	0 (0)	75.42 (247.38)	1.18 (3.35)

As demonstrated in this analysis for the given assumptions and conditions in this example, the Corrugated HDPE pipe manufactured with virgin materials offered life cycle cost savings of 34% over RCP and 45% over CMP, while Corrugated HDPE pipe manufactured with recycled materials offered life cycle cost savings of 39% over RCP and 49% over CMP. Corrugated PP pipe offered life cycle cost savings of 29% over RCP and 41% over CMP.

This was just an example for one pipe diameter and the actual savings will clearly vary based on local costs and pipe availability. Additionally, the service life assumptions and maintenance costs are dependent upon installation conditions and the specific material types selected. For example, a polymer-coated or aluminized CMP pipe system may offer comparable service life to HDPE and RCP pipe systems in certain service conditions. However, the purpose of this example was to illustrate the potential for cost savings associated with Corrugated HDPE pipes manufactured both with and without recycled materials and with Corrugated PP pipes manufactured with virgin materials. This example demonstrates one of the reasons why municipalities may be interested in specifying these types of pipe systems, or at least in allowing these materials to be part of their matrix of available pipe options for a given application.

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6. Pluimer, M. (2013). Recycled Materials Survey with Corrugated HDPE Pipe Manufacturers.

Appendix A - Design Guide

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 Chapter 7, Structural Design 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 7 of the PPI Drainage Handbook for further explanation of the design methodology, design variables, and resulting factor of safety. For the purpose of simplicity and clarity, only English units are used within this Appendix.

A.1 Design Example 1 – Deep Fill Over PP Storm Drain

A.1.1 Background, Installation Parameters & Design Steps

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% Standard Proctor Density (SPD) rather than compacted crushed rock (Class I) material. The contractor has approached a design engineer to provide the final design.

Installation Parameters

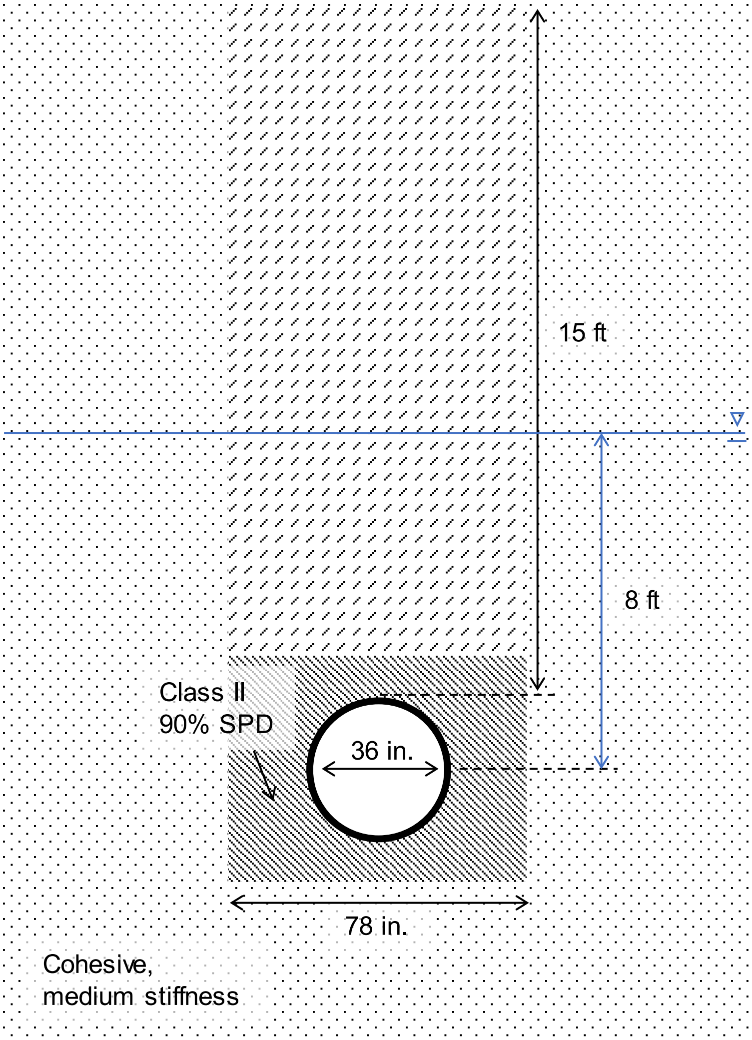
The site design drawings provide the following information.

Parameter	Value	Reference [1]
Embedment material	Class II 90% SPD	7.3.2, 7.3.3
Native soil	Cohesive, medium stiffness	7.3.3
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, g_s	120 pcf	7.4.1
Backfill soil saturated unit weight, g_{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 the 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, App C For the purpose of simplicity and clarity, only English units are used within this Appendix.
Pipe moment of inertia, I_p	1.52 $in^4/in.$	7.2.3
Pipe stiffness	40 psi	7.2.2



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[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.

A.1.2 Loading

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

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

$$\gamma_b = \gamma_{sat} - \gamma_w$$

(Eqn. 7.8)

$$\gamma_b = 136\,pcf - 62.4\,pcf$$

$$\gamma_b = 74\,pcf$$

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

$$P_{sp} = \left[H - \left(H_w - 0.5D_o\right)\right]\gamma_s + \left(H_w - 0.5D_o + 0.11D_o\right)\gamma_b$$

(Eqn. 7.10)

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

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

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.

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

$$P_w = \gamma_w K_w H_w \ \ \leq \ \gamma_w \left(H + \frac{D_o}{2} \right) \qquad \text{(Eqn. 7.12)}$$

$$P_w = 62.4\,pcf * 1.3 * 8\,ft$$

$$P_w = 649\,psf = 4.5\,psi$$

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. Special loads of greater magnitude, such as railroad, plane, or large crane loading, would still require consideration at this depth.

A.1.3 Hoop Thrust

Per Table 7.6, 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.

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

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

$$M_{sb} = 1637\,psi$$

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 7.9, a constrained modulus of 1,500 psi is appropriate for the medium stiffness cohesive native soil (M_{sn}).

Interpolate from Table 7.10 to determine the soil support combining factor (S_c).

$$B_d / D_o = 78in / 41in = 1.9$$

$$M_{sn} / M_{sb} = 1500\,psi / 1637\,psi = 0.92$$

		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

$$S_c = 0.967$$

$$M_s = composite\,constrained\,modulus$$

$$M_s = S_c M_{sb} \qquad \text{(Eqn. 7.7)}$$

$$M_s = 0.967 * 1637\,psi$$

$$M_s = 1583\,psi$$

Per Table 7.1, 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 (Hoop Thrust Design).

$$S_H = \frac{\phi_s M_s R}{E_{lt} A_g} \qquad \text{(Eqn. 7.23)}$$

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

$$S_H = 1.51$$

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

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

$$VAF = 0.70$$ (Eqn. 7.24)

The factored thrust at the pipe springline is calculated as described in Section 7.5.2. The maximum Strength I Limit State Load Factor for vertical earth load (γ_{EV}) from Table 7.14 is considered.

$$T_D = \mathit{factored\ dead\ and\ hydrostatic\ thrust\ force}$$

$$T_D = \eta_{EV}\left(\gamma_{EV} K_2 \left(VAF\right) P_{sp} + \gamma_{WA} P_w\right)\frac{D_o}{2}$$ (Eqn. 7.25)

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

$$T_D = 410\,lbf / in$$

The maximum factored hoop thrust strain is calculated as described in Section 7.5.2.

$$\varepsilon_c = \mathit{factored\ thrust\ strain}$$

$$\varepsilon_c = \frac{T_D}{A_{eff} E_{lt}}$$ (Eqn. 7.30)

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

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

The maximum factored hoop thrust strain is checked against the limit as described in Section 7.5.2. The resistance factor (f_t) is taken from Table 7.15. The compression strain limit (ε_{yc}) is taken from Table 7.3 for PP.

$$\varepsilon_c \leq \phi_t \varepsilon_{yc} \qquad \text{(Eqn. 7.31)}$$

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

A.1.4 Thrust Plus Bending

Per Table 7.16, 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.

$$D_f = shape\ factor$$

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

$$D_f = 3.42$$

The service pipe thrust at the springline is calculated as described in Section 7.5.2 with all load factors excluded.

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

$$T_{SD} = \left(K_2\left(VAF\right)P_{sp}+P_w\right)\frac{D_o}{2} \qquad \text{(Eqn. 7.25)}$$

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

$$T_{SD} = 245lbf\ /\ in$$

The service hoop thrust strain is calculated as described in Section 7.5.2 using the gross section area.

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

$$\varepsilon_{SC} = \frac{T_{SD}}{A_g E_{lt}} \tag{Eqn. 7.30}$$

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

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

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.

$$\varepsilon_f = factored\ flexural\,strain$$

$$\varepsilon_f = \gamma_{EV} D_f \frac{c}{R}\left(\frac{\delta D_i - \varepsilon_{SC} D}{D}\right) \tag{Eqn. 7.32}$$

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

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

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.

$$\varepsilon_f + \varepsilon_c \le \phi_t 1.5 \varepsilon_{yc} \qquad \text{(Eqn. 7.34)}$$

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

$$4.2\% \le 5.6\%$$

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 is not applicable.

A.1.5 Deflection

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

$$\Delta_t = pipe\, deflection$$

$$\Delta_t = \frac{K_B D_L P_{sp} D_o}{\frac{E_{lt} I_p}{R^3} + 0.061 M_s} + \frac{K_B C_L P_L D_o}{\frac{E_{st} I_p}{R^3} + 0.061 M_s} + 2R\varepsilon_{sc} \qquad \text{(Eqn. 7.21)}$$

$$\Delta_t = \frac{0.1 * 1.5 * 10.7\,psi * 41in}{\frac{28000\,psi * 1.52\,in^4/in}{(19.25in)^3} + 0.061 * 1583\,psi} + 2 * 19.25in * 1.3\%$$

$$\Delta_t = 1.27in$$

$$\Delta_t \le \delta D_i \qquad \text{(Eqn. 7.22)}$$

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

$$1.27in \le 1.80in$$

A.1.6 Global Buckling

Global buckling is checked as described in Section 7.5.2. The resistance factor (ϕ_{bck}) is taken from Table 7.15.

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

$$R_h = \frac{11.4}{11 + D/12H} \qquad \text{(Eqn. 7.36)}$$

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

$$R_h = 1.02$$

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

$$\varepsilon_{bck} = \frac{1.2C_n\left(E_{lt}I_p\right)^{\frac{1}{3}}}{A_{eff}E_{lt}}\left[\frac{\phi_s M_s\left(1-2\nu\right)}{\left(1-\nu\right)^2}\right]^{\frac{2}{3}} R_h \qquad \text{(Eqn. 7.35)}$$

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

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

$$\varepsilon_c \le \phi_{bck}\varepsilon_{bck} \qquad \text{(Eqn. 7.37)}$$

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

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

A.1.7 Flexibility Factor

The flexibility factor is checked as described in Section 7.5.2. Per Table 7.1, the short-term creep modulus of the pipe PP material (E_{st}) is 175 ksi.

$$FF = flexibility\ factor$$

$$FF = \frac{D^2}{E_{st} I_p} \leq 0.095 in / lbf \qquad \text{(Eqn. 7.38)}$$

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

$$FF = 0.006 in / lbf \leq 0.095 in / lbf$$

A.1.8 Buoyancy

The buoyant force is checked as described in Section 7.5.2. The Strength I Limit State Load Factor for hydrostatic load (γ_{WA}) and minimum for vertical earth load (γ_{EVmin}) are from Table 7.14. The resistance factor (f_b) is taken from Table 7.15.

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

$$F_{bd} = \frac{\pi}{4} D_o{}^2 \gamma_w \qquad \text{(Eqn. 7.39)}$$

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

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

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

$$F_{br} = P_{sp} D_o \qquad \text{(Eqn. 7.40)}$$

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

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

$$\gamma_{WA} F_{bd} \leq \gamma_{EVmin} \phi_b F_{br} \qquad \text{(Eqn. 7.41)}$$

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

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

A.1.9 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

A.2 Design Example 2 – Shallow Fill Over HDPE Culvert

A.2.1 Background, Installation Parameters & Design Steps

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
Native soil	Medium, cohesive material	7.3.3
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
Pipe inside diameter, D_i	48 in. (4 ft)	
Soil moist unit weight, g_s	120 pcf	7.4.1
Height of water table, H_w	Below springline	

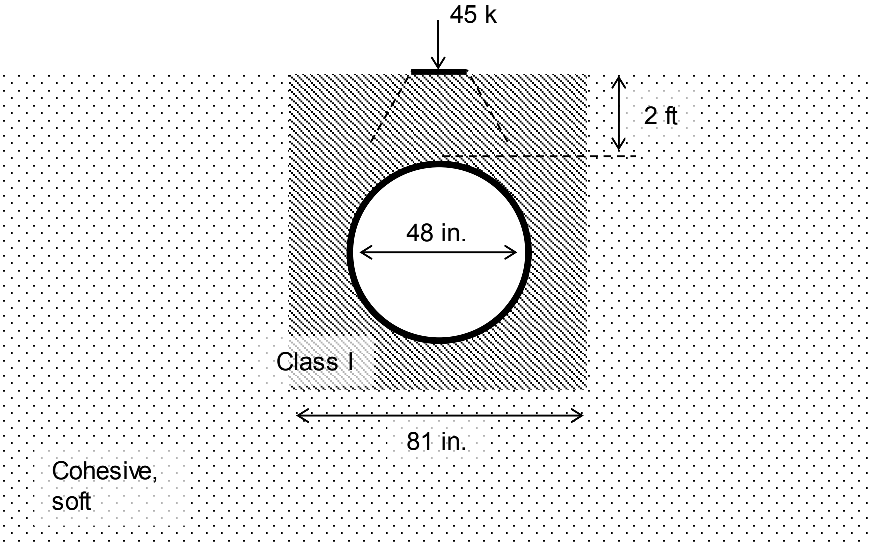
All references are to relevant sections of the PPI Drainage Handbook

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
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
Design life	75 years	



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.

A.2.2 Loading

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

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

$$P_{sp} = \left(H + 0.11D_o\right)\gamma_s \text{ for } H_w \leq 0.5D_o, \qquad \text{(Eqn. 7.9)}$$

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

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

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, construction live loads may be evaluated using a similar application method as that shown for the Design Truck in Section 7.4.3, 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. Due to large axle spacing (8 ft) and shallow cover (2 ft), there is no interaction between the wheel loads (Eqn. 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.

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

$$l_d = l_t + LLDF * H \quad l_d = l_t + LLDF * H \qquad \text{(Eqn. 7.16)}$$

$$l_d = 18in + 1.15 * 24in$$

$$l_d = 45.6in$$

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

$$w_d = w_t + LLDF * H + 0.06D_i \qquad \text{(Eqn. 7.17)}$$

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

$$w_d = 48.5in$$

$$P_L = vertical\ pressure\ at\ top\ of\ pipe\ due\ to\ live\ load$$

$$P_L = \frac{P_{surf}}{w_d l_d} \qquad \text{(Eqn. 7.20)}$$

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

$$P_L = 20.3psi = 2930psf$$

A.2.3 Hoop Thrust

Per Table 7.5, 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 7.9, a constrained modulus of 1,500 psi is appropriate for the medium native soil (M_{sn}). Use Table 7.10 to determine the soil support combining factor (S_c).

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

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

$$S_c = 0.53$$

$$M_s = S_c M_{sb} \qquad \text{(Eqn. 7.7)}$$

$$M_s = 0.53 * 3500 psi$$

$$M_s = 1850 psi$$

Per Table 7.1, 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.

$$S_H = \frac{\phi_s M_s R}{E_{lt} A_g} \qquad \text{(Eqn. 7.23)}$$

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

$$S_H = 7.98$$

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

$$VAF = 0.76 - 0.71\left[\frac{7.98 - 1.17}{27.98 + 2.92}\right]$$ (Eqn. 7.24)

$$VAF = 0.32$$

The corrugation effective area (A_{eff}) is calculated based on stub compression test results, as described in Section 7.2.3. The time factor (K_t) is taken from Table 7.4. The yield strength (F_y) is taken from Table 7.2.

$$A_{eff} = \frac{P_{st}K_t}{F_y} \leq A_g$$ (Eqn. 7.2)

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

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

The factored thrust at the pipe springline is calculated as described in Section 7.5.2. The construction vehicle is treated as an owner-specified load with reduced live load factor as described in Section 7.5.4.

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

$$T_D = \eta_{EV}\left(\gamma_{EV}K_2\left(VAF\right)P_{sp}\right)\frac{D_o}{2}$$ (Eqn. 7.25)

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

$$T_D = 36 lbf / in$$

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

$$F_1 = \max\left(\frac{0.75D_o}{l_d}, \frac{15}{D_i}, 1.0\right)$$ (Eqn. 7.27)

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

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

$$F_2 = \frac{0.95}{1+0.6S_H}$$ (Eqn. 7.28)

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

$$C_L = live\,load\ coefficient$$

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

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

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

$$T_L = \eta_{LL}\gamma_{LL}C_L F_1 F_2 P_L \frac{D_o}{2}$$ (Eqn. 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.

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

$$\varepsilon_c = \frac{T_D}{A_{eff} E_{lt}} + \frac{T_L}{A_{eff} E_{PE24}} \qquad \text{(Eqn. 7.30)}$$

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

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

The maximum factored hoop thrust strain is checked against the limit as described in Section 7.5.2. The resistance factor (ϕ_t) is taken from Table 7.15. The compression strain limit (ε_{yc}) is taken from Table 7.3 for HDPE.

$$\varepsilon_c \le \phi_t \varepsilon_{yc} \qquad \text{(Eqn. 7.31)}$$

$$1.1\% \le 1.0 * 4.1\%$$

A.2.4 Thrust Plus Bending

Since the pipe stiffness (PS) is not provided, it is calculated as described in Section 7.2.2.

$$PS = \frac{E_{st} I_p}{0.149 R^3} \qquad \text{(Eqn. 7.1)}$$

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

$$PS = 25.5\text{psi}$$

Per Table 7.16, 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 with all load factors excluded.

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

$$T_{SD} = \left(K_2 (VAF) P_{sp} + P_w\right) \frac{D_o}{2} \qquad \text{(Eqn. 7.25)}$$

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

$$T_{SD} = 18lbf / in$$

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

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

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

$$T_{SL} = 76lbf / in$$

The service hoop thrust strain is calculated as described in Section 7.5.2 using the gross section area.

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

$$\varepsilon_{SC} = \frac{T_{SD}}{A_g E_{lt}} + \frac{T_{SL}}{A_g E_{PE24}} \qquad \text{(Eqn. 7.30)}$$

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

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

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.

$$\varepsilon_f = factored\ flexural\ strain$$

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

(Eqn. 7.32)

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

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

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.

$$\varepsilon_f + \varepsilon_c \le \phi_t 1.5 \varepsilon_{yc}$$

(Eqn. 7.34)

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

$$3.3\% \le 6.1\%$$

To check net tension strain, as described in Section 7.5.2, the minimum thrust strain is calculated using the minimum dead load factor and the reduction factor for thrust at the crown ($K_2 = 0.6$).

$$T_D = \eta_{EV}\left(\gamma_{EV} K_2 \left(VAF\right) P_{sp}\right)\frac{D_o}{2} \qquad \text{(Eqn. 7.25)}$$

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

$$T_D = 22 lbf / in$$

$$\varepsilon_c = \frac{22 lbf / in}{21000 psi * 0.33 \, {in^2}/{in}} + \frac{103 lbf / in}{50000 psi * 0.33 \, {in^2}/{in}} \qquad \text{(Eqn. 7.30)}$$

$$\varepsilon_c = 0.9\%$$

The hoop thrust strain is checked against the limit as described in Section 7.5.2. The resistance factor for flexure (ϕ_f) is taken from Table 7.15. The compression strain limit (ε_{yt}) is taken from Table 7.3 for HDPE.

$$\left|\varepsilon_f - \varepsilon_c\right| \leq \phi_f \varepsilon_{yt} \qquad \text{(Eqn. 7.30)}$$

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

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

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).

A.2.5 Deflection

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

$$\Delta_t = pipe\, deflection$$

$$\Delta_t = \frac{K_B D_L P_{sp} D_o}{\frac{E_{lt} I_p}{R^3} + 0.061 M_s} + \frac{K_B C_L P_L D_o}{\frac{E_{PE24} I_p}{R^3} + 0.061 M_s} + 2R\varepsilon_{sc} \qquad \text{(Eqn. 7.21)}$$

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

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

$$\Delta_t = 1.3in$$

$$\Delta_t \le \delta D_i \qquad \text{(Eqn. 7.22)}$$

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

$$1.3in < 2.4in$$

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

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

A.2.6 Global Buckling

Global buckling is checked as described in Section 7.5.2.

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

$$R_h = \frac{11.4}{11 + {D}/{12H}} \qquad \text{(Eqn. 7.36)}$$

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

$$R_h = 0.87$$

$v = Poisson\ Ratio$, estimated as 0.3 per Section 7.5.2

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

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

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

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

$$\varepsilon_c \le \phi_{bck}\varepsilon_{bck} \qquad \text{(Eqn. 7.37)}$$

$$1.1\% \le 0.7*23\%$$

$$1.1\% \le 15.9\%$$

A.2.7 Flexibility factor

The flexibility factor is checked as described in Section 7.5.2.

$$FF = flexibility\ factor$$

$$FF = \frac{D^2}{E_{st}I_p} \le 0.095in/lbf \qquad \text{(Eqn. 7.38)}$$

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

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

A.2.8 Buoyancy

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

A.2.9 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