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September 30, 2022

Ms. Ann Bekta
Wisconsin Department of Natural Resources
Janesville Service Center
2514 Morse Street
Janesville, WI 53545-0249

Subject: Waste Management of Wisconsin, Inc. - Orchard Ridge Recycling and Disposal Facility
Proposed Eastern Expansion, Southern Unit
Plan of Operation - Addendum 2
Village of Menomonee Falls, Waukesha County, Wisconsin
License No. 4491

Dear Ms. Bekta:

On behalf of Waste Management of Wisconsin, Inc. (WMWI), this letter to respond to the Wisconsin Department of Natural Resources (WDNR)'s request to revise the pipe strength calculations to utilize a higher unit weight of waste.

Per a discussion between WMWI and the WDNR, it was requested that the pipe strength calculations submitted in the Orchard Ridge Recycling and Disposal Facility, Proposed Eastern Expansion, Southern Unit (Southern Unit) Plan of Operation, dated February 2022 (Feb 2022 POO) be revised using a conservative and theoretical unit of weight of wet waste of 119 pounds per cubic foot (pcf) that was previously presented in the 2018 East Expansion Plan of Operation's stability analysis.

Per WDNR's request, the shallow and deep loading conditions of the pipe strength calculations were revised to account for the requested unit weight of waste. These updated calculations are provided in **Attachment 2**. WMWI and TRC trust that we have provided the information requested by the Department. Per the Department's request, only electronic versions of this Addendum have been provided.

WMWI is requesting that the WDNR review and provide a complete Plan of Operation determination for the proposed Southern Unit. Please feel free to contact Tyler Field, at 262-443-2240 or Michael Amstadt at 608-358-2669 with any questions regarding this document.

Sincerely,

TRC

Michael Amstadt

Michael Amstadt, P.E.
Principal Project Manager

cc: David Buser, Alicia Zewicki, Tyler Field, Ryan Baeten, Brett Coogan – electronic copies only

List of Enclosures:

- Attachment 1: Addendum Certification Statement
- Attachment 2: Revised Pipe Strength Calculations

Attachment 1

Addendum Certification Statement

Certification

I, ______________________________, hereby certify that I am a registered professional engineer
Michael Amstadt

in the State of Wisconsin, registered in accordance with the requirements of Chapter A-E 4, Wisconsin Administrative Code; that this document has been prepared in accordance with the Rules of Professional Conduct in Chapter A-E 8, Wisconsin Administrative Code; and that, to the best of my knowledge, all information contained in this document is correct and the document was prepared in compliance with all applicable requirements in Chapters NR 500 to NR 538, Wisconsin Administrative Code.

Michael Amstadt

Digitally signed by Michael Amstadt
Date: 2022.09.30 15:36:55 -05'00'

Attachment 2

Revised Pipe Strength Calculations

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PROJECT/PROPOSAL NAME	PREPARED		CHECKED		PROJECT/PROPOSAL NO.
Waste Management of Wisconsin, Inc. Orchard Ridge RDF Eastern Expansion, Southern Unit Plan of Operation	By: J. Bell A. Rowley B. Kahnk	Date: 8/12/2021 11/10/2021 9/28/2022	By: A. Rowley B. Kahnk M. Amstadt	Date: 8/13/2021 11/10/2021 9/29/2022	324442.0005

PIPE STRENGTH CALCULATIONS

Purpose:

Pipe strength calculations demonstrate that the proposed piping for the Orchard Ridge Recycling and Disposal Facility (Orchard Ridge RDF) Eastern Expansion, Southern Unit (Southern Unit) will withstand the loading conditions during construction and long-term performance.

Methodology:

Loading:

There are two sources of loading on the leachate collection system piping: live (vehicular) loading and soil loading in the vertical prism above the pipe. Soil loading is determined by summing the product of the unit weight and corresponding thickness of each layer. For wheeled equipment, the Boussinesq equation gives the resulting pressure on the pipe from a concentrated load anywhere above the pipe. Area loading, e.g. tracked equipment, is determined using the Area Loading equation. Each equation considers the depth of fill above the pipe and surface loading to determine the resulting load on the pipe. Live loads from tracked (area load) and wheeled (point load) equipment are compared to determine worst case loading (PPI, 2009).

Pipe Strength:

Pipe perforations cause a reduction in pipe strength. To account for this reduction, loading values from soil and equipment are increased using the Loading Adjustment Equation for Perforations (Duffy, 2006). Adjusted loading values are incorporated into calculations to assess deflection, wall compression, buckling, and, for shallow fill, “membrane” bending of the pipe crown:

- Deflection due to the load on the pipe is calculated using the Modified Iowa equation for depths less than 50 feet. The resulting value is compared to recommended values (PPI, 2009).
- Compressive stress in the wall of the pipe is determined using the Wall Compression equation. This equation uses the Standard Dimension Ratio (SDR) to evaluate the effects from loading on the pipe. The resulting value is compared to allowable values for the pipe material (PPI, 2009).
- Allowable pressure to prevent buckling is calculated using Unconstrained Pipe Wall Buckling equation for shallow fills less than 4 feet and Constrained Pipe Wall Buckling equation for fills greater than 4 feet. Resulting values are compared to pressure from live loads and soil loads.
- Allowable loading to prevent the “membrane” bending effect in shallow fills of the pipe crown is determined using the Watkins equation. Resulting values are compared to pressure from live loads and soil loads.

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For pipes buried under fills greater than 50 feet, live loads are neglected, and Watkins' method is used to calculate ring compressive force and pipe deflection from the weight of the soil column. Ring compressive force is compared to the long-term compressive strength demonstrates the pipes' abilities to withstand crushing. Watkins' method states that the deflection of the pipe is limited by the deflection of the sideslope soil surrounding the pipe and calculating the potential deflection of the sideslope soils determines the maximum possible deflection of the pipe. Percent deflection due to the soil column is compared to recommended values for cleanout operational equipment (Harrison and Watkins, 1996).

Pipe strength properties (i.e. pipe stiffness, wall thickness, and pipe flexural modulus) and the support provided by the soil (i.e. soil modulus) are used to determine the maximum allowable confined buckling pressure and compared to the maximum dead load due to the column of waste and cover soil over the pipe.

Assumptions:

Loading Conditions

Three loading conditions were analyzed for both the 6-inch leachate collection pipe and 18-inch leachate sideslope riser pipe. These loading conditions are summarized below.

- Short-term loading during the construction of the select aggregate drainage layer: Select aggregate fill depth over the pipes is minimized (2.5-feet over leachate collection pipes and 3 feet over the sideslope riser pipe) to maximize the live load from equipment. For the short-term strength analysis, the maximum live load on the pipe during construction (minimum fill cover depth) uses the following typical equipment specifications (Caterpillar, 2010):
  - Cat D11 Dozer
  - Cat 745 C Dump Truck

  Note that equipment loads used in this calculation were selected to represent extreme loading conditions on the proposed pipe to confirm the pipe strength. During construction, equipment used during construction will be restricted to meet the requirements of s. NR 504.06(3)(h).
- Shallow long-term loading of the pipes under select aggregate fill (depths listed above) and waste fill (2 feet) was also analyzed. Under this condition, cover is minimized and live-loading is maximized.
- Deep long-term loading:
  - For the leachate collection pipe:
    - 2.5 feet of select aggregate fill,
    - 220.7 feet of waste fill,

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    - 2 feet of select compacted clay, and
    - 2.5 feet of general fill (rooting zone).

  Depths are maximized under this condition. The maximum waste thickness proposed is located within the vertical overlay area in the East Expansion limits of waste. The maximum waste thickness within the lateral expansion area is 198 feet; therefore, the critical condition is located within the vertical overlay area.

  - For the sideslope riser pipe:
    - 3 feet of select aggregate fill,
    - 56.9 feet of waste fill,
    - 2 feet of select compacted clay, and
    - 2.5 feet of general fill (rooting zone).

    Depths are maximized under this condition. The maximum waste thickness proposed is located within the lateral expansion area outside the limits of waste for the East Expansion. The maximum waste thickness within the East Expansion vertical is 51.90 feet; therefore, the critical condition is located within the lateral expansion area.

- For the long-term strength analysis, live loads are considered insignificant at high fill depths. Therefore, the maximum static load on the pipe following closure uses the following soil layer unit weights (based on laboratory analysis and TRC experience):
  - Rooting zone and topsoil = 115 pounds per cubic foot (pcf)
  - Select Compacted Clay (Soil Barrier Layer) = 130 pcf
  - Waste Fill = 119 pcf
  - Select Aggregate Fill = 125 pcf

It should be noted that the waste fill unit weight is considered highly conservative. Proposed final waste grades and final cover configuration were used to calculate the worst-case dead load conditions after closure.

Piping Applications

- For the Southern Unit, pipe strength was considered for the following applications:
  - 6-inch SDR 11 HDPE perforated leachate collection pipe
  - 18-inch SDR 11 HDPE perforated sideslope riser pipe

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- Open-channel flow conditions without pressure (*i.e.*, pipes do not run full) are assumed for all pipes.
- Flexible plastic pipe can withstand varying levels of deflection based on material and thickness; however, a range of 5-7.5% has become the standard allowable deflection to prevent access issues during cleaning or servicing (LamsonVylon, 2010).
- Longitudinal strain of the piping is not applicable at the Southern Unit. Straining is caused by inconsistent support by the pipe bedding (Harrison and Watkins, 1996); however, under continuous bedding and construction on firm foundation, it is disregarded.
- Tangential strain of the piping is not applicable at the Southern Unit. It is calculated on the basis of deflection, pipe Standard Deflection Ratio (SDR), and pipe outside diameter. The allowable tangential strain of the pipes will not be exceeded if the allowable deflection is not exceeded (Harrison and Watkins, 1996).

Pipe Compressive Strength and Thermal Compatibility

With atmospheric temperatures during summer construction potentially reaching 100 ºF, and elevated temperature due to biological activity within the landfill, a temperature de-rating factor of 0.78 was applied to the standard compressive strength for a high-density polyethylene (HDPE) pipe to obtain a compressive strength of [780 psi (1,000 psi x 0.78)] for the short-term and long-term analyses (PPI, 2009).

Pipe Perforations

When the perforation open space of the ½-inch diameter holes (spaced at 180 degree intervals around the pipe laterally and every 6 inches for the 6-inch SDR 11 HDPE perforated leachate collection pipe or spaced at 90 degree intervals around the pipe laterally and every 6 inches for the 18-inch SDR 11 HDPE perforated sideslope riser pipe) was compared to the surface area of the pipes, the perforation open area was deemed to be minimal. The effect of perforations is negligible in comparison to the factors of safety that was achieved for deflection and ring compression calculations. See attachments for further calculations.

Pipe Bedding

The bedding constrained modulus (one-dimensional modulus) used to determine the deflection of the soil in Watkins' method is defined by soil type, compaction, and stress level applied to the soil. For the proposed pipes embedded in select aggregate fill, the stress level at each piping application assumes the bedding material is placed at a minimum of 90 percent of the material's modified proctor value (95 percent standard proctor value). The result is a constrained soil modulus of 6,500 psi (PPI, 2009). For soil reaction modulus, values between 1500 psi and 2500 psi were used for the shallow burial scenarios, dependent on the burial depth condition.

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Results:

Construction Loading

The results of Boussinesq's formula show that compressive strength of the HDPE pipe will not be exceeded during construction conditions with a minimum of 18 inches of cover material over the pipe before loading is applied. For each piping application, the calculated pipe loading is well below the allowable compressive strength of 1000 psi for HDPE at 73°F.

Post Closure Long Term Loading

The results of Watkins' Method show that the ring compression force does not exceed the maximum allowable design long-term compressive strength of 780 psi for the proposed pipes. Additionally, based on the anticipated deflection of the sideslope soil, the allowable deflection of 5-7.5% was also not exceeded. Lastly, the maximum design load for each piping application was less than each pipe's respective calculated allowable buckling pressure. Based on these results, the proposed pipe design is adequate and appropriate for the anticipated construction, operation, and closure loading conditions. See tables below for the result summaries of the different conditions.

6-inch SDR 11 HDPE Perforated Leachate Collection Pipe

Pipe Information	Crushing		Deflection		Buckling	
Pipe Description	Ring Compressive Force (psi)	Allowable Compressive Strength (PSI)	Estimated Deflection (%)	Allowable Deflection (%)	Maximum Design Load (psi)	Allowable Buckling Pressure (psi)
Construction Loading	233	1,000	2.4	7.50	42	705
Long-Term Shallow Fill Loading	95	780	1.6	7.50	17	323
Long-Term Deep Fill Loading	774	780	3.9	7.50	251	588

18-inch SDR 11 HDPE Perforated Side-Slope Riser Pipe

Pipe Information	Crushing		Deflection		Buckling	
Pipe Description	Ring Compressive Force (psi)	Allowable Compressive Strength (psi)	Estimated Deflection (%)	Allowable Deflection (%)	Maximum Design Load (psi)	Allowable Buckling Pressure (psi)
Construction Loading	255	1,000	2.6	7.50	46	705
Long—Term Shallow Fill Loading	110	780	1.1	7.50	20	705
Long-Term Deep Fill Loading	588	780	6.2	7.50	107	472

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References:

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Chevron Phillips Chemical Co. LP. 2011. CP Chem Performance Pipe. The Performance Pipe Engineering Manual.

Harrison, S. and R.K. Watkins. 1996. HDPE Leachate Collection Pipe Design by Fundamentals of Mechanics. Presented at the Nineteenth International Madison Waste Conference, Department of Engineering Professional Development, University of Wisconsin Madison. September 25-26, 1996.

ISCO. 2012. HDPE Typical Physical Properties. http:// www.isco-pipe.com/media. Accessed on November 16, 2012.

The Plastic Pipe Institute (PPI). 2009. Handbook of Polyethylene Pipe: Second Edition.

Uni-bell PVC Pipe Association. 2001. Uni-bell Handbook of PVC Pipe Design and Construction. 4th edition. Dallas: Uni-bell PVC Pipe Association.

Watkins, Reynold K. 1987. Structural performance of perforated and slotted high-density polyethylene pipes under high soil cover. Department of Civil Engineering, Utah State University.

Calculations

- Summary Tables
  - 6-inch SDR 11 HDPE Pipe
  - 18-inch SDR 11 HDPE Pipe (Riser Pipe)
- Construction Loading:
  - 6-inch SDR 11 HDPE Pipe:
    - Live Loading: Boussinesq, Area (Track) Loading
    - Pipe Strength: Loading Adjustment for Perforations
    - Pipe Resistance: Modified Iowa, Wall Compression, Unconstrained Buckling, Watkins
  - 18-inch SDR 11 HDPE Pipe (Riser Pipe):
    - Live Loading: Boussinesq, Area (Track) Loading
    - Pipe Strength: Loading Adjustment for Perforations
    - Pipe Resistance: Modified Iowa, Wall Compression, Unconstrained Buckling, Watkins
- Long Term Loading (Shallow):
  - 6-inch SDR 11 HDPE Pipe:
    - Live Loading: Boussinesq, Area (Track) Loading
    - Pipe Strength: Loading Adjustment for Perforations
    - Pipe Resistance: Modified Iowa, Wall Compression, Luscher
  - 18-inch SDR 11 HDPE Pipe (Riser Pipe):
    - Live Loading: Boussinesq, Area (Track) Loading
    - Pipe Strength: Loading Adjustment for Perforations
    - Pipe Resistance: Modified Iowa, Wall Compression, Luscher
- Long Term Loading (Deep):
  - 6-inch SDR 11 HDPE Pipe:
    - Live Loading: Boussinesq, Area (Track) Loading
    - Pipe Strength: Loading Adjustment for Perforations
    - Pipe Resistance: Harrison and Watkins, Wall Compression, Luscher
  - 18-inch SDR 11 HDPE Pipe (Riser Pipe):
    - Live Loading: Boussinesq, Area (Track) Loading
    - Pipe Strength: Loading Adjustment for Perforations
    - Pipe Resistance: Harrison and Watkins, Wall Compression, Luscher

Summary Tables

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PROJECT / PROPOSAL NAME / LOCATION:		PROJECT / PROPOSAL NO.	
Orchard Ridge- Pipe Strength Calculations		324442.0005.0000	
PREPARED/UPDATED BY:	J. Bell; A. Rowley; B. Kahnk	DATE:	8/12/2021; 11/10/2021; 9/28/2022
CHECKED BY:	A. Rowley; M. Dogan	DATE:	8/12/2021; 9/28/2022

Summary Table for Leachate Collection Piping:

PIPE TYPE	NOMINAL DIAMETER (in)	OUTSIDE DIAMETER (in)	DIMENSION RATIO, DR	MINIMUM THICKNESS (in)	AVERAGE INSIDE DIAMETER (in)
6 inch SDR 11 HDPE Pipe	6	6.625	11	0.602	5.349

CONSTRUCTION LOADING				
FAILURE TYPE	**LOADING VALUE**	**ALLOWABLE VALUE**	**FACTOR OF SAFETY**	**ALLOWABLE VALUE REFERENCE**
Deflection	2.4%	7.50%	NA	Allowable Deflection of 7.5% provides a factor of safety of approximately 3 against reverse curvature of the pipe
Wall Compression (psi)	233	1000	4.3	Allowable value was determined from the pipe material designation code PE3608
Constrained Buckling above Groundwater Level	42	705	16.7	Factor of safety against buckling should be greater than 2.0
Pipe Crown Membrane Bending (psi)	42	767	18.1	Loading value must not exceed the allowable value for the pipe.
LONG-TERM LOADING UNDER SHALLOW FILL CONDITION				
FAILURE TYPE	**LOADING VALUE**	**ALLOWABLE VALUE**	**FACTOR OF SAFETY**	**ALLOWABLE VALUE REFERENCE**
Deflection	1.6%	7.50%	NA	Allowable Deflection of 7.5% provides a factor of safety of approximately 3 against reverse curvature of the pipe
Wall Compression	95	780	8.2	Allowable value was determined from the pipe material designation code PE3608
Constrained Buckling above Groundwater Level	17	323	18.7	Factor of safety against buckling should be greater than 2.5
LONG-TERM LOADING UNDER DEEP FILL CONDITION				
FAILURE TYPE	**LOADING VALUE**	**ALLOWABLE VALUE**	**FACTOR OF SAFETY**	**ALLOWABLE VALUE REFERENCE**
Deflection	3.9%	7.50%	NA	Allowable Deflection of 7.5% provides a factor of safety of approximately 3 against reverse curvature of the pipe
Wall Compression (psi)	774	780	1.0	Allowable value was determined from the pipe material designation code PE3608
Constrained Buckling above Groundwater Level	251	588	2.3	Factor of safety against buckling should be greater than 2.0

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CHECKED BY:	A. Rowley; B. Kahnk; M. Dogan	DATE:	8/12/2021; 11/10/2021

Summary Table for Riser Pipe:

PIPE TYPE	NOMINAL DIAMETER (in)	OUTSIDE DIAMETER (in)	DIMENSION RATIO, DR	MINIMUM THICKNESS (in)	AVERAGE INSIDE DIAMETER (in)
18 inch SDR 11 HDPE Pipe	18	18	11	1.636	14.532

CONSTRUCTION LOADING				
FAILURE TYPE	LOADING VALUE	ALLOWABLE VALUE	FACTOR OF SAFETY	ALLOWABLE VALUE REFERENCE
Deflection	2.6%	7.50%	NA	Allowable Deflection of 7.5% provides a factor of safety of approximately 3 against reverse curvature of the pipe
Wall Compression (psi)	255	1000	3.9	Allowable value was determined from the pipe material designation code PE3608
Constrained Buckling above Groundwater Level	46	705	15.2	Factor of safety against buckling should be greater than 2.0
Pipe Crown Membrane Bending (psi)	46	161	3.5	Loading value must not exceed the allowable value for the pipe.
LONG-TERM LOADING NDER SHALLOW FILL CONDITION				
FAILURE TYPE	LOADING VALUE	ALLOWABLE VALUE	FACTOR OF SAFETY	ALLOWABLE VALUE REFERENCE
Deflection	1.1%	7.50%	NA	Allowable Deflection of 7.5% provides a factor of safety of approximately 3 against reverse curvature of the pipe
Wall Compression (psi)	110	780	7.1	Allowable value was determined from the pipe material designation code PE3608
Constrained Buckling above Groundwater Level	20	705	35.3	Factor of safety against buckling should be greater than 2.5
LONG-TERM LOADING UNDER DEEP FILL CONDITION				
FAILURE TYPE	LOADING VALUE	ALLOWABLE VALUE	FACTOR OF SAFETY	ALLOWABLE VALUE REFERENCE
Deflection	6.2%	7.50%	NA	Allowable Deflection of 7.5% provides a factor of safety of approximately 3 against reverse curvature of the pipe
Wall Compression (psi)	588	780	1.3	Allowable value was determined from the pipe material designation code PE3608
Constrained Buckling above Groundwater Level	107	431	4.0	Factor of safety against buckling should be greater than 2.5

Construction Loading

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CHECKED BY:	A. Rowley; B. Kahnk	DATE:	8/12/2021: 11/10/2021	REVISION

PIPE STRENGTH CALCULATIONS
MINIMUM COVER
CONSTRUCTION LOADING

Live-Loading Inputs:

Soil Inputs:

SOIL LAYER	SOIL TYPE	UNIT WEIGHT (pcf)	SOIL LAYER THICKNESS (FT)	SOIL LAYER LOAD (psi)
1	Select Aggregate Fill	125	2.5	2.17

Wheeled Vehicle Inputs:

VEHICLE NO.	VEHICLE DESCRIPTION	NO. OF WHEELS	WEIGHT DISTRIBUTION	OPERATING WEIGHT (lbs)	WEIGHT PER WHEEL (lbs)
1	CAT 745 C Dump Truck	6	0.34/0.33/0.33	164024	27,884

=> For wheeled vehicles the CAT 745 C Dump Truck load is the largest, thus use 27884 lb. to determine PL

Tracked Vehicle Inputs:

VEHICLE NO.	VEHICLE TYPE	OPERATING WEIGHT PER TRACK (lbs)	TRACK WIDTH (ft)	TRACK LENGTH (ft)	WEIGHT PER TRACK (lbs)	GROUND CONTACT AREA PER TRACK (in^2)	DISTRIBUTED LOAD PER TRACK (psi)
2	CAT D11 Dozer	114924	2.33	14.6	57,462	4,899	12

=> For tracked vehicles the 12 psi load is the largest, thus use 12 psi to determine PLS

Live-Loading Calculation:

Boussinesq Equation for Point (Wheeled) Loading (PPI, 2009):

$$P_L = \frac{3\, I_z\, P\, H^3}{2\, \pi\, r^5} \qquad r = (X^2 + H^2)^{1/2}$$

VARIABLE	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
Iz	Road Type Impact Factor	2	unitless	For dirt roads (PPI, 2009)
P	Concentrated Surface Load	27884	lbs	CAT 745 C Dump Truck has the largest load
H	Depth of Soil Cover	30	in	User input "Minimum Soil Cover"
X	Horizontal Distance of Wheel from Pipe	0	in	r = H for one wheel directly above the pipe
r	Radial Distance of Load from Pipe	30	in	Wheel is directly above the pipe
PL	Vertical Pressure Acting on the Pipe	**29.6**	**psi**	Calculated Value

Area (Track) Loading Equation (PPI, 2009):

$$P_{LS} = 4\, I_V\, w_s$$

VARIABLE	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
ws	Distributed Pressure of the Track	12	psi	CAT D11 Dozer has the largest distributed load
M	1/2 Track Width	1.2	ft	Calculated Value
M/H	Ratio of Track Width to Soil Depth	0.5	ft/ft	Calculated Value
N	1/2 Track Length	7.3	ft	Calculated Value
N/H	Ratio of Track Length to Soil Depth	Infinite	ft/ft	Calculated Value
Iv	Influence value for distributed loads	0.137	unitless	Table 1 from PPI, 2009.
PLS	Vertical pressure due to the track area load	**6.6**	**psi**	Calculated Value

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Point Load		**Area Load**	
29.6	>	6.6	psi

=> Use Point Load

Pipe Strength Reduction From Perforations

Loading Adjustment Equation for Perforations (Inverse of Pipe Strength Reduction) (Duffy, 2006):

$$P_{LV} = \frac{12 * (P_L or P_{LS})}{12 - D * N} \qquad P_E = \frac{12 * \sum[(Soil\ Layer\ Depth) * (Soil\ Layer\ Unit\ Weight)]}{12 - D * N}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
D	Perforation Diameter	0.5	in	1/2" perforation
N	Number of Perforations / Foot of Pipe	6	ft	2 perforation pairs every 6 inches
P_{LV}	Modified Vertical Live Load	39.4	psi	Calculated
P_E	Modified Vertical Soil Load	2.89	psi	Calculated

Pipe Resistance Inputs:

PIPE NUMBER	PIPE TYPE	NOMINAL DIAMETER (in)	OUTSIDE DIAMETER (in)	DIMENSION RATIO, DR	MINIMUM THICKNESS (in)	AVERAGE INSIDE DIAMETER (in)
1	6 inch SDR 11 HDPE Pipe	6	6.625	11	0.602	5.349

Pipe Resistance Calculations:

Pipe Wall Deflection

Modified Iowa Equation Eq 3-10 Chapter 6 (PPI, 2009):

$$\% \frac{X}{D} = \left(\frac{K_{BED} L_{DL} P_E + K_{BED} P_{LV}}{\left(\frac{2E}{3}\right)\left(\frac{1}{(DR-1)}\right)^\wedge 3 + 0.061 F_S E'} \right)$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
K_{BED}	Bedding Factor	0.1	unitless	Typical value
L_{DL}	Deflection Lag Factor	1	unitless	Vehicle loading dominates. Use $L_{DL} = 1$
P_E	Vertical Load from Soil Pressure	2.89	psi	Calculated
P_{LV}	Vertical Load from Vehicle	39.4	psi	Calculated
E	Apparent Modulus of Elastic Pipe	125000	psi	PE3XXX Table B.2.1 from PPI, 2009
E'	Modulus of Soil Reaction	1500	psi	Crushed rock. From Table 3-8 PPI, 2009 is 3000 psi. 1500psi is conservative
F_S	Soil Support Factor	1	unitless	Table 3-10 (trench width>>OD of pipe) from PPI, 2009
DR	Dimension Ratio (OD/t)	11	in/in	Pipe Manufacturer
X/D	**% Deflection**	**2.42%**	**percent**	**Calculated, Allowable Value is 7.5%**

Pipe Wall Compression (Crushing Fig 3-1B Ch 6):

Wall Compression Equation Eq 3-13 Chapter 6 (PPI, 2009):

$$S = \frac{(P_E + P_{LV})DR}{2} < S_{allowable}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
P_E	Vertical Load from Soil Pressure	2.89	psi	Calculated
P_{LV}	Vertical Load from Vehicle	39.4	psi	Calculated
DR	Dimension Ratio (OD/t)	11	in/in	Pipe Manufacturer
S	Pipe Wall Compressive Stress	233	psi	Calculated
$S_{allowable}$	Allowable Compressive Stress	1000	psi	at 73deg F Table C.1 (PE 3408) from PPI, 2009
	Factor of Safety	**4.29**		

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Pipe Wall Buckling:

Luscher Equation for Constrained Buckling Below Ground Water Level Eq 3-15 Chapter 6 (PPI, 2009):

$$P_{WC} = 5.65 * \sqrt{R * B' * E' * \left(\frac{E}{12 * (DR-1)^3}\right)} \qquad B' = \frac{1}{1 + 4e^{-0.065H}} \qquad Factor\ of\ Safety = \frac{P_{Wc}}{P_{LV} + P_E}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
R	Buoyancy Reduction Factor	1	unitless	Height of groundwater above the pipe is zero. Thus, R = 1
H	Total depth of soil load above pipe	0.21	ft	User input "Soil Inputs" table
E'	Modulus of Soil Reaction	1500	psi	Crushed rock. From Table 3-8 PPI, 2009 is 3000 psi. 1500psi is conservative
E	Apparent Modulus of Elasticity	125000	psi	50-years, PE3XXX Table B.1.1 from PPI, 2009
DR	Dimension Ratio	11	in/in	Pipe Manufacturer
B'	Soil Support Factor	0.20	unitless	Calculated
P_{WC}	Allowable Buckling Pressure	318	psi	Calculated
	Factor of Safety	**7.5**		

Pipe Wall Buckling:

PVC manual page 7.38 EQ 7.18 for Constrained Buckling in Dry Soil (above groundwater level)

Pcr= 2*Fo*E/ { [1-nu^2][DR-1]^3} **Pb = 1.15 Sqrt[Pcr E']**

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
DR	Dimension Ratio	11	in/in	Pipe Manufacturer
E	Apparent Modulus of Elasticity	125000	psi	PE3XXX Table B.2.1 from PPI, 2009
E'	Modulus of Soil Reaction	1500	psi	Crushed rock. From Table 3-8 PPI, 2009 is 3000 psi. 1500psi is conservative
D_I	Average Inside Diameter	5.349	in	Pipe Manufacturer
D_{Min}	Minimum Inside Diameter	5.261	in	Pipe Manufacturer
μ	Poisson's Ratio	0.45	unitless	Chapter 3, Appendix D from PPI, 2009
F_O	Ovality Correction Factor	0.8	unitless	Determined from Figure 3-9 from PPI, 2009
P_{CR}	Critical Buckling Pressure (unconstrained)	251	psi	Calculated
P_B	Buckling Pressure	705		
	Unconstrained Factor of Safety	5.92		
	Factor of Safety	**16.66**		**Required FS >= 2.0**

Membrane Bending Effect due to Shallow Cover Live-Loading

Watkins Equation Eq 3-19 Chapter 6 (PPI, 2009):

$$P_{WAT} = \frac{12\, w\, (KH)^2}{D_O} + \frac{7387\, I}{D_O^2\, c}\left(S_{MAT} - \frac{w\, D_O\, H}{288\, A}\right) \qquad K = \frac{1 + SIN(\phi)}{1 - SIN(\phi)} \qquad Factor\ of\ Safety = \frac{P_{WU}}{P_{LV} + P_E}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
w =	Unit Weight of Bedding Material	125	pcf	Soil Inputs Table
Do =	Pipe Outside Diameter	6.625	in	Pipe Manufacturer
H =	Depth of Cover	2.5	ft	Soil Inputs Table
I =	Moment of Inertia of the Pipe Wall	0.050166667	in^4/in	Thickness divided by 12 for DR pipes
A =	Wall Thickness	0.602	in	A parameter is thickness for DR pipes
c =	Outer Centroid of Wall Centroid	0.301	in	Thickness divided by 2 for DR pipes
S_{MAT} =	Material Yield Strength	3200	psi	Pipe Manufacturer
ϕ =	Friction Angle of Bedding Material	36	degrees	Estimated value for aggregate
K =	Passive Earth Pressure Coefficient of Bed.	3.85		Calculated
P_{WAT} =	Allowable Load Pressure, psf	767	psf	Calculated
	Factor of Safety	**18.11**		

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PIPE STRENGTH CALCULATIONS
MINIMUM COVER
CONSTRUCTION LOADING FOR RISER PIPE

Live-Loading Inputs:

Soil Inputs:

SOIL LAYER	SOIL TYPE	UNIT WEIGHT (pcf)	SOIL LAYER THICKNESS (FT)	SOIL LAYER LOAD (psi)
1	Select Aggregate Fill	125	3	2.60

Wheeled Vehicle Inputs:

VEHICLE NO.	VEHICLE DESCRIPTION	NO. OF WHEELS	WEIGHT DISTRIBUTION	OPERATING WEIGHT (lbs)	WEIGHT PER WHEEL (lbs)
1	CAT 745 C Dump Truck	6	0.34/0.33/0.33	164024	27,884

=> For wheeled vehicles the CAT 745 C Dump Truck load is the largest, thus use 27884 lb. to determine PL

Tracked Vehicle Inputs:

VEHICLE NO.	VEHICLE TYPE	OPERATING WEIGHT PER TRACK (lbs)	TRACK WIDTH (ft)	TRACK LENGTH (ft)	WEIGHT PER TRACK (lbs)	GROUND CONTACT AREA PER TRACK (in^2)	DISTRIBUTED LOAD PER TRACK (psi)
2	CAT D11 Dozer	114924	2.33	14.6	57,462	4,899	12

=> For tracked vehicles the 12 psi load is the largest, thus use 12 psi to determine PLS

Live-Loading Calculation:

Boussinesq Equation for Point (Wheeled) Loading (PPI, 2009):

$$P_L = \frac{3\, I_z\, P\, H^3}{2\, \pi\, r^5} \qquad r = (X^2 + H^2)^{1/2}$$

VARIABLE	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
Iz	Road Type Impact Factor	2	unitless	For dirt roads (PPI, 2009)
P	Concentrated Surface Load	27884	lbs	CAT 745 C Dump Truck has the largest load
H	Depth of Soil Cover	36	in	User input "Minimum Soil Cover"
X	Horizontal Distance of Wheel from Pipe	0	in	r = H for one wheel directly above the pipe
r	Radial Distance of Load from Pipe	36	in	Wheel is directly above the pipe
PL	Vertical Pressure Acting on the Pipe	**20.5**	**psi**	Calculated Value

Area (Track) Loading Equation (PPI, 2009):

$$P_{LS} = 4\, I_V\, w_s$$

VARIABLE	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
ws	Distributed Pressure of the Track	12	psi	CAT D11 Dozer has the largest distributed load
M	1/2 Track Width	1.2	ft	Calculated Value
M/H	Ratio of Track Width to Soil Depth	0.4	ft/ft	Calculated Value
N	1/2 Track Length	7.3	ft	Calculated Value
N/H	Ratio of Track Length to Soil Depth	Infinite	ft/ft	Calculated Value
Iv	Influence value for distributed loads	0.115	unitless	Table 1 from PPI, 2009.
PLS	Vertical pressure due to the track area load	**5.5**	**psi**	Calculated Value

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Point Load		Area Load	
20.5	>	5.5	psi

=> Use Point Load

Pipe Strength Reduction From Perforations

Loading Adjustment Equation for Perforations (Inverse of Pipe Strength Reduction) (Duffy, 2006):

$$P_{LV} = \frac{12 * (P_L or P_{LS})}{12 - D * N} \qquad P_E = \frac{12 * \sum[(Soil\ Layer\ Depth) * (Soil\ Layer\ Unit\ Weight)]}{12 - D * N}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
D	Perforation Diameter	0.5	in	1/2" perforation
N	Number of Perforations / Foot of Pipe	12	ft	4 perforation sets every 6 inches
P_{LV}	Modified Vertical Live Load	41.1	psi	Calculated
P_E	Modified Vertical Soil Load	5.21	psi	Calculated

Pipe Resistance Inputs:

PIPE NUMBER	PIPE TYPE	NOMINAL DIAMETER (in)	OUTSIDE DIAMETER (in)	DIMENSION RATIO, DR	MINIMUM THICKNESS (in)	AVERAGE INSIDE DIAMETER (in)
1	18 inch SDR 11 HDPE Pipe	18	18	11	1.636	14.532

Pipe Resistance Calculations:

Pipe Wall Deflection

Modified Iowa Equation Eq 3-10 Chapter 6 (PPI, 2009):

$$\% \frac{X}{D} = \left(\frac{K_{BED} L_{DL} P_E + K_{BED} P_{LV}}{\left(\frac{2E}{3}\right)\left(\frac{1}{(DR-1)}\right)^{\wedge}3 + 0.061 F_S E'} \right)$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
K_{BED}	Bedding Factor	0.1	unitless	Typical value
L_{DL}	Deflection Lag Factor	1	unitless	Vehicle loading dominates. Use $L_{DL} = 1$
P_E	Vertical Load from Soil Pressure	5.21	psi	Calculated
P_{LV}	Vertical Load from Vehicle	41.1	psi	Calculated
E	Apparent Modulus of Elastic Pipe	125000	psi	PE3XXX Table B.2.1 from PPI, 2009
E'	Modulus of Soil Reaction	1500	psi	Crushed rock. From Table 3-8 PPI, 2009 is 3000 psi. 1500 psi is conservative
F_S	Soil Support Factor	1	unitless	Table 3-10 (trench width>>OD of pipe) from PPI, 2009
DR	Dimension Ratio (OD/t)	11	in/in	Pipe Manufacturer
X/D	**% Deflection**	**2.65%**	**percent**	**Calculated, Allowable Value is 7.5%**

Pipe Wall Compression (Crushing Fig 3-1B Ch 6):

Wall Compression Equation Eq 3-13 Chapter 6 (PPI, 2009):

$$S = \frac{(P_E + P_{LV})DR}{2} < S_{allowable}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
P_E	Vertical Load from Soil Pressure	5.21	psi	Calculated
P_{LV}	Vertical Load from Vehicle	41.1	psi	Calculated
DR	Dimension Ratio (OD/t)	11	in/in	Pipe Manufacturer
S	Pipe Wall Compressive Stress	255	psi	Calculated
$S_{allowable}$	Allowable Compressive Stress	1000	psi	at 73deg F Table C.1 (PE 3408) from PPI, 2009
	Factor of Safety	**3.93**		

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Pipe Wall Buckling:

<u>Luscher Equation for Constrained Buckling Below Ground Water Level Eq 3-15 Chapter 6 (PPI, 2009):</u>

$$P_{WC} = 5.65 * \sqrt{R * B' * E' * \left(\frac{E}{12 * (DR-1)^3}\right)} \qquad B' = \frac{1}{1+4e^{-0.065H}} \qquad Factor\ of\ Safety = \frac{P_{Wc}}{P_{LV}+P_E}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
R	Buoyancy Reduction Factor	1	unitless	Height of groundwater above the pipe is zero. Thus, R = 1
H	Total depth of soil load above pipe	0.25	ft	User input "Soil Inputs" table
E'	Modulus of Soil Reaction	1500	psi	Crushed rock. From Table 3-8 PPI, 2009 is 3000 psi. 1500 psi is conservative
E	Apparent Modulus of Elasticity	125000	psi	50-years, PE3XXX Table B.1.1 from PPI, 2009
DR	Dimension Ratio	11	in/in	Pipe Manufacturer
B'	Soil Support Factor	0.20	unitless	Calculated
P_{WC}	Allowable Buckling Pressure	318	psi	Calculated
	Factor of Safety	**6.9**		

Pipe Wall Buckling:

<u>PVC manual page 7.38 EQ 7.18 for Constrained Buckling in Dry Soil (above groundwater level)</u>

Pcr= 2*Fo*E/ { [1-nu^2][DR-1]^3} **Pb = 1.15 Sqrt[Pcr E']**

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
DR	Dimension Ratio	11	in/in	Pipe Manufacturer
E	Apparent Modulus of Elasticity	125000	psi	PE3XXX Table B.2.1 from PPI, 2009
E'	Modulus of Soil Reaction	1500	psi	Crushed rock. From Table 3-8 PPI, 2009 is 3000 psi. 1500 psi is conservative
D_I	Average Inside Diameter	14.532	in	Pipe Manufacturer
D_{Min}	Minimum Inside Diameter	14.251	in	Pipe Manufacturer
μ	Poisson's Ratio	0.45	unitless	Chapter 3, Appendix D from PPI, 2009
F_O	Ovality Correction Factor	0.8	unitless	Determined from Figure 3-9 from PPI, 2009
P_{CR}	Critical Buckling Pressure (unconstrained)	251	psi	Calculated
P_B	Buckling Pressure	705		
	Unconstrained Factor of Safety	5.42		
	Factor of Safety	**15.23**		**Required FS >= 2.0**

Membrane Bending Effect due to Shallow Cover Live-Loading

<u>Watkins Equation Eq 3-19 Chapter 6 (PPI, 2009):</u>

$$P_{WAT} = \frac{12\, w\, (KH)^2}{D_O} + \frac{7387\, I}{D_O^2\, c}\left(S_{MAT} - \frac{w\, D_O\, H}{288\, A}\right) \qquad K = \frac{1+SIN(\phi)}{1-SIN(\phi)} \qquad Factor\ of\ Safety = \frac{P_{WU}}{P_{LV}+P_E}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
w =	Unit Weight of Bedding Material	125	pcf	Soil Inputs Table
Do =	Pipe Outside Diameter	18	in	Pipe Manufacturer
H =	Depth of Cover	3	ft	Soil Inputs Table
I =	Moment of Inertia of the Pipe Wall	0.136333333	in^4/in	Thickness divided by 12 for DR pipes
A =	Wall Thickness	1.636	in	A parameter is thickness for DR pipes
c =	Outer Centroid of Wall Centroid	0.818	in	Thickness divided by 2 for DR pipes
S_{MAT} =	Material Yield Strength	3200	psi	Pipe Manufacturer
ϕ =	Friction Angle of Bedding Material	36	degrees	Estimated value for aggregate
K =	Passive Earth Pressure Coefficient of Bed.	3.85		Calculated
P_{WAT} =	Allowable Load Pressure, psf	161	psf	Calculated
	Factor of Safety	**3.48**		

Long Term Loading (Shallow)

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PIPE STRENGTH CALCULATIONS
4.5 FT SHALLOW FILL
LONG-TERM LOADING

Live-Loading Inputs:

Soil Inputs:

SOIL LAYER	SOIL TYPE	UNIT WEIGHT (pcf)	SOIL LAYER THICKNESS (ft)	SOIL LAYER LOAD (psi)
1	Select Aggregate Fill	125	2.5	2.17
2	Waste Fill	119	2.0	1.65

Wheeled Vehicle Inputs:

VEHICLE NO.	VEHICLE DESCRIPTION	NO. OF WHEELS	WEIGHT DISTRIBUTION	OPERATING WEIGHT (lbs)	WEIGHT PER WHEEL (lbs)
1	CAT 745 C Dump Truck	6	0.34/0.33/0.33	164024	27,884
2	Ford F-150 Truck	4	0.25	5014	1,254

=> For wheeled vehicles the CAT 745 C Dump Truck load is the largest,
thus use 27884.08 lb. to determine PL

Tracked Vehicle Inputs:

VEHICLE NO.	VEHICLE TYPE	OPERATING WEIGHT PER TRACK (lbs)	TRACK WIDTH (ft)	TRACK LENGTH (ft)	WEIGHT PER TRACK (lbs)	GROUND CONTACT AREA PER TRACK (in^2)	DISTRIBUTED LOAD PER TRACK (psi)
3	CAT D11 Dozer	114924	2.33	14.6	57,462	4,900	12

=> For tracked vehicles the 12 psi load is the largest,
thus use 12 psi to determine PLS

Live-Loading Calculation:

Equations (PPI, 2009):

Boussinesq Equation for Point (Wheeled) Loading Eq 3-4 (PPI, 2009):

$$P_L = \frac{3\, I_z\, P\, H^3}{2\,\pi\, r^5} \qquad r = (X^2 + H^2)^{1/2}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
Iz	Road Type Impact Factor	2	unitless	For dirt roads (PPI, 2009)
P	Concentrated Surface Load	27884.08	lbs	CAT 745 C Dump Truck has the largest load
H	Depth of Soil Cover	54	in	User input "Soil Inputs" table
X	Horizontal Distance of Wheel from Pipe	0	in	r = H for one wheel directly above the pipe
r	Radial Distance of Load from Pipe	54	in	Wheel is directly above the pipe
PL	Vertical Pressure Acting on the Pipe	**9.13**	**psi**	Calculated Value

Area (Track) Loading Equation Eq 3-8 (PPI, 2009):

$$P_{LS} = 4\, I_V\, w_s$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
ws	Distributed Pressure of the Track	12	psi	CAT D11 Dozer has the largest distributed load
M	1/2 Track Width	1.2	ft	Figure 3-5 in PPI, 2009
M/H	Ratio of Track Width to Soil Depth	0.300	ft/ft	Table 1 from PPI, 2009
N	1/2 Track Length	7.3	ft	Figure 3-5 in PPI, 2009
N/H	Ratio of Track Length to Soil Depth	1.620	ft/ft	Table 1 from PPI, 2009
Iv	Influence value for distributed loads	0.086	unitless	Table 1 from PPI, 2009.
PLS	Vertical pressure due to the track area load	**4.13**	**psi**	Calculated Value

Point Load		Area Load	
9.13	>	4.13	psi

=> Use Point Load

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Pipe Strength Reduction From Perforations

Loading Adjustment Equation for Perforations (Inverse of Pipe Strength Reduction) (Duffy, 2006):

$$P_{LV} = \frac{12 * (P_L or P_{LS})}{12 - D * N} \qquad P_E = \frac{12 * \sum[(Soil\ Layer\ Depth) * (Soil\ Layer\ Unit\ Weight)]}{12 - D * N}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
D	Perforation Diameter	0.5	in	1/2" perforation
N	Number of Perforations / Foot of Pipe	6	ft	2 perforation pairs every 6 inches
P_{LV}	Modified Vertical Live Load	12.18	psi	Calculated
P_E	Modified Vertical Soil Load	5.1	psi	Calculated

Pipe Resistance Inputs:

PIPE NUMBER	PIPE TYPE	NOMINAL DIAMETER (in)	OUTSIDE DIAMETER (in)	DIMENSION RATIO, DR	MINIMUM THICKNESS (in)	AVERAGE INSIDE DIAMETER (in)
1	6 inch SDR 11 HDPE Pipe	6	6.625	11	0.602	5.349

Pipe Resistance Calculations:

Pipe Wall Deflection:

Modified Iowa Equation Eq 3-10 Chapter 6 (PPI, 2009):

$$\% \frac{X}{D} = \left(\frac{K_{BED} L_{DL} P_E + K_{BED} P_{LV}}{\left(\frac{2E}{3}\right)\left(\frac{1}{(DR-1)^3}\right) + 0.061 F_S E'} \right)$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
K_{BED}	Bedding Factor	0.1	unitless	Typical value
L_{DL}	Deflection Lag Factor	1	unitless	Vehicle loading dominates. Use L_{DL} = 1
P_E	Vertical Load from Soil Pressure	5.1	psi	Calculated
P_{LV}	Vertical Load from Vehicle	12.18	psi	Calculated
E	Apparent Modulus of Elastic Pipe	28000	psi	50-years, PE3XXX Table B.1.1 from PPI, 2009
E'	Modulus of Soil Reaction	1500	psi	Crushed rock. From Table 3-8 PPI, 2009
F_S	Soil Support Factor	1	unitless	Table 3-10 (trench width>>OD of pipe) from PPI, 2009
DR	Dimension Ratio (OD/t)	11	in/in	Pipe Manufacturer
X/D	**% Deflection**	**1.57%**	**percent**	**Calculated, Allowable Value is 7.5%**

Pipe Wall Compression (Crushing Fig 3-1B Ch 6):

Wall Compression Equation Eq 3-13 Chapter 6 (PPI, 2009):

$$S = \frac{(P_E + P_{LV})DR}{2} < S_{allowable}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
P_E	Vertical Load from Soil Pressure	5.1	psi	Calculated
P_{LV}	Vertical Load from Vehicle	12.18	psi	Calculated
DR	Dimension Ratio (OD/t)	11	in/in	Pipe Manufacturer
S	Pipe Wall Compressive Stress	95	psi	Calculated
$S_{allowable}$	Allowable Compressive Stress	780	psi	Table C.1 (PE 3408) from PPI, 2009
	Factor of Safety	**8.21**		

Pipe Wall Buckling:

PVC manual page 7.38 EQ 7.18 for Constrained Buckling

Pcr= 2*Fo*E/ { [1-nu^2][DR-1]^3} **Pb = 1.15 Sqrt[Pcr E']**

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
DR	Dimension Ratio	11	in/in	Pipe Manufacturer
E	Apparent Modulus of Elasticity	28000	psi	PE3XXX Table B.2.1 from PPI, 2009
E'	Modulus of Soil Reaction	1500	psi	Crushed rock. From Table 3-8 PPI, 2009
D_I	Average Inside Diameter	5.349	in	Pipe Manufacturer
μ	Poisson's Ratio	0.45	unitless	Chapter 3, Appendix D from PPI, 2009
F_O	Ovality Correction Factor	0.75	unitless	Determined from Figure 3-9 from PPI, 2009
P_{CR}	A. Critical Buckling Pressure (unconstrained)	53	psi	Calculated
P_B	Allowable Buckling Pressure	323		
	Unconstrained Factor of Safety	3.05		
	Factor of Safety	**18.71**		**Required FS >= 2.0**

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PIPE STRENGTH CALCULATIONS
5 FT SHALLOW FILL
LONG-TERM LOADING

Live-Loading Inputs:

Soil Inputs:

SOIL LAYER	SOIL TYPE	UNIT WEIGHT (pcf)	SOIL LAYER THICKNESS (FT)	SOIL LAYER LOAD (psi)
1	Select Aggregate Fill	125	3	2.60
2	Waste Fill	119	2	1.65

Recommended min cover thickness is 18 "

Chapter 6, p. 224 (PPI 2009)

Wheeled Vehicle Inputs:

VEHICLE NO.	VEHICLE DESCRIPTION	NO. OF WHEELS	WEIGHT DISTRIBUTION	OPERATING WEIGHT (lbs)	WEIGHT PER WHEEL (lbs)
1	CAT 745 C Dump Truck	6	0.34/0.33/0.33	164024	27,884
2	Ford F-150 Truck	4	0.25	5014	1,254

=> For wheeled vehicles the CAT 745 C Dump Truck load is the largest,
thus use 27884 lb. to determine PL

Tracked Vehicle Inputs:

VEHICLE NO.	VEHICLE TYPE	OPERATING WEIGHT PER TRACK (lbs)	TRACK WIDTH (ft)	TRACK LENGTH (ft)	WEIGHT PER TRACK (lbs)	GROUND CONTACT AREA PER TRACK (in^2)	DISTRIBUTED LOAD PER TRACK (psi)
2	CAT D11 Dozer	114924	2.33	14.6	57,462	4,899	12

=> For tracked vehicles the 12 psi load is the largest,
thus use 12 psi to determine PLS

Live-Loading Calculation:

Boussinesq Equation for Point (Wheeled) Loading (PPI, 2009):

$$P_L = \frac{3\, I_z\, P\, H^3}{2\, \pi\, r^5} \qquad r = (X^2 + H^2)^{1/2}$$

VARIABLE	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
Iz	Road Type Impact Factor	2	unitless	For dirt roads (PPI, 2009)
P	Concentrated Surface Load	27884	lbs	CAT 745 C Dump Truck has the largest load
H	Depth of Soil Cover	60	in	User input "Minimum Soil Cover"
X	Horizontal Distance of Wheel from Pipe	0	in	r = H for one wheel directly above the pipe
r	Radial Distance of Load from Pipe	60	in	Wheel is directly above the pipe
PL	Vertical Pressure Acting on the Pipe	**7.4**	**psi**	Calculated Value

Area (Track) Loading Equation (PPI, 2009):

$$P_{LS} = 4\, I_V\, w_s$$

VARIABLE	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
ws	Distributed Pressure of the Track	12	psi	CAT D11 Dozer has the largest distributed load
M	1/2 Track Width	1.2	ft	Calculated Value
M/H	Ratio of Track Width to Soil Depth	0.2	ft/ft	Calculated Value
N	1/2 Track Length	7.3	ft	Calculated Value
N/H	Ratio of Track Length to Soil Depth	1.46	ft/ft	Calculated Value
Iv	Influence value for distributed loads	0.062	unitless	Table 1 from PPI, 2009.
PLS	Vertical pressure due to the track area load	**3.0**	**psi**	Calculated Value

Point Load		Area Load	
7.4	>	3.0	psi

=> Use Point Load

PROJECT / PROPOSAL NAME / LOCATION: Orchard Ridge- Pipe Strength Calculations				PROJECT / PROPOSAL NO. 324442.0005.0000
PREPARED/UPDATED BY:	J. Bell; A. Rowley; B. Kahnk	DATE:	8/12/2021; 11/10/2021; 9/28/2022	FINAL
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Pipe Strength Reduction From Perforations

Loading Adjustment Equation for Perforations (Inverse of Pipe Strength Reduction) (Duffy, 2006):

$$P_{LV} = \frac{12 * (P_L or P_{LS})}{12 - D * N} \qquad P_E = \frac{12 * \sum[(Soil\ Layer\ Depth) * (Soil\ Layer\ Unit\ Weight)]}{12 - D * N}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
D	Perforation Diameter	0.5	in	1/2" perforation
N	Number of Perforations / Foot of Pipe	12	ft	4 perforation sets every 6 inches
P_{LV}	Modified Vertical Live Load	14.8	psi	Calculated
P_E	Modified Vertical Soil Load	5.21	psi	Calculated

Pipe Resistance Inputs:

PIPE NUMBER	PIPE TYPE	NOMINAL DIAMETER (in)	OUTSIDE DIAMETER (in)	DIMENSION RATIO, DR	MINIMUM THICKNESS (in)	AVERAGE INSIDE DIAMETER (in)
1	18 inch SDR 11 HDPE Pipe	18	18	11	1.636	14.532

Pipe Resistance Calculations:

Pipe Wall Deflection

Modified Iowa Equation Eq 3-10 Chapter 6 (PPI, 2009):

$$\% \frac{X}{D} = \left(\frac{K_{BED} L_{DL} P_E + K_{BED} P_{LV}}{\left(\frac{2E}{3}\right)\left(\frac{1}{(DR-1)}\right)^3 + 0.061 F_S E'} \right)$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
K_{BED}	Bedding Factor	0.1	unitless	Typical value
L_{DL}	Deflection Lag Factor	1	unitless	Vehicle loading dominates. Use $L_{DL} = 1$
P_E	Vertical Load from Soil Pressure	5.21	psi	Calculated
P_{LV}	Vertical Load from Vehicle	14.8	psi	Calculated
E	Apparent Modulus of Elastic Pipe	125000	psi	50-years, PE3XXX Table B.2.1 from PPI, 2009
E'	Modulus of Soil Reaction	1500	psi	Crushed rock. From Table 3-8 PPI, 2009 is 3000 psi. 1500psi is conservative
F_S	Soil Support Factor	1	unitless	Table 3-10 (trench width>>OD of pipe) from PPI, 2009
DR	Dimension Ratio (OD/t)	11	in/in	Pipe Manufacturer
X/D	**% Deflection**	**1.14%**	**percent**	**Calculated, Allowable Value is 7.5%**

Pipe Wall Compression (Crushing Fig 3-1B Ch 6):

Wall Compression Equation Eq 3-13 Chapter 6 (PPI, 2009):

$$S = \frac{(P_E + P_{LV})DR}{2} < S_{allowable}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
P_E	Vertical Load from Soil Pressure	5.21	psi	Calculated
P_{LV}	Vertical Load from Vehicle	14.8	psi	Calculated
DR	Dimension Ratio (OD/t)	11	in/in	Pipe Manufacturer
S	Pipe Wall Compressive Stress	110	psi	Calculated
$S_{allowable}$	Allowable Compressive Stress	780	psi	at 73deg F Table C.1 (PE 3408) from PPI, 2009
	Factor of Safety	**7.09**		

PROJECT / PROPOSAL NAME / LOCATION: Orchard Ridge- Pipe Strength Calculations					PROJECT / PROPOSAL NO. 324442.0005.0000
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Pipe Wall Buckling:

Luscher Equation for Constrained Buckling Below Ground Water Level Eq 3-15 Chapter 6 (PPI, 2009):

$$P_{WC} = 5.65 * \sqrt{R * B' * E' * \left(\frac{E}{12 * (DR-1)^3}\right)}$$

$$B' = \frac{1}{1 + 4e^{-0.065H}}$$

$$Factor\ of\ Safety = \frac{P_{Wc}}{P_{LV} + P_E}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
R	Buoyancy Reduction Factor	1	unitless	Height of groundwater above the pipe is zero. Thus, R = 1
H	Total depth of soil load above pipe	0.25	ft	User input "Soil Inputs" table
E'	Modulus of Soil Reaction	1500	psi	Crushed rock. From Table 3-8 PPI, 2009 is 3000 psi. 1500psi is conservative
E	Apparent Modulus of Elasticity	125000	psi	50-years, PE3XXX Table B.1.1 from PPI, 2009
DR	Dimension Ratio	11	in/in	Pipe Manufacturer
B'	Soil Support Factor	0.20	unitless	Calculated
P_{WC}	Allowable Buckling Pressure	318	psi	Calculated
	Factor of Safety	**15.9**		

Pipe Wall Buckling:

PVC manual page 7.38 EQ 7.18 for Constrained Buckling in Dry Soil (above groundwater level)

Pcr= 2*Fo*E/ { [1-nu^2][DR-1]^3}

Pb = 1.15 Sqrt[Pcr E']

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
DR	Dimension Ratio	11	in/in	Pipe Manufacturer
E	Apparent Modulus of Elasticity	125000	psi	PE3XXX Table B.2.1 from PPI, 2009
E'	Modulus of Soil Reaction	1500	psi	Crushed rock. From Table 3-8 PPI, 2009 is 3000 psi. 1500psi is conservative
D_I	Average Inside Diameter	14.532	in	Pipe Manufacturer
D_{Min}	Minimum Inside Diameter	14.522	in	Pipe Manufacturer
μ	Poisson's Ratio	0.45	unitless	Chapter 3, Appendix D from PPI, 2009
F_O	Ovality Correction Factor	0.8	unitless	Determined from Figure 3-9 from PPI, 2009
P_{CR}	Critical Buckling Pressure (unconstrained)	251	psi	Calculated
P_B	Buckling Pressure	705		
	Unconstrained Factor of Safety	12.54		
	Factor of Safety	**35.26**		**Required FS >= 2.0**

Membrane Bending Effect due to Shallow Cover Live-Loading

Watkins Equation Eq 3-19 Chapter 6 (PPI, 2009):

$$P_{WAT} = \frac{12\ w\ (KH)^2}{D_O} + \frac{7387\ I}{D_O^2\ c}\left(S_{MAT} - \frac{w\ D_O\ H}{288\ A}\right)$$

$$K = \frac{1 + SIN(\phi)}{1 - SIN(\phi)}$$

$$Factor\ of\ Safety = \frac{P_{WU}}{P_{LV} + P_E}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
w =	Unit Weight of Bedding Material	125	pcf	Soil Inputs Table
Do =	Pipe Outside Diameter	18	in	Pipe Manufacturer
H =	Depth of Cover	5	ft	Soil Inputs Table
I =	Moment of Inertia of the Pipe Wall	0.136333333	in^4/in	Thickness divided by 12 for DR pipes
A =	Wall Thickness	1.636	in	A parameter is thickness for DR pipes
c =	Outer Centroid of Wall Centroid	0.818	in	Thickness divided by 2 for DR pipes
S_{MAT} =	Material Yield Strength	3200	psi	Pipe Manufacturer
ϕ =	Friction Angle of Bedding Material	36	degrees	Estimated value for aggregate
K =	Passive Earth Pressure Coefficient of Bed.	3.85		Calculated
P_{WAT} =	Allowable Load Pressure, psf	298	psf	Calculated
	Factor of Safety	**14.92**		

Long Term Loading (Deep)

PROJECT / PROPOSAL NAME / LOCATION: Orchard Ridge- Pipe Strength Calculations				PROJECT / PROPOSAL NO. 324442.0005.0000
PREPARED/UPDATED BY:	J. Bell; A. Rowley; B. Kahnk	DATE:	8/12/2021; 11/10/2021; 9/28/2022	FINAL
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PIPE STRENGTH CALCULATIONS
227.7 FT DEEP FILL
LONG-TERM LOADING

Live-Loading Inputs:

Soil Inputs:

SOIL LAYER	SOIL TYPE	UNIT WEIGHT (pcf)	SOIL LAYER THICKNESS (ft)	SOIL LAYER LOAD (psi)
1	Rooting zone/topsoil	115	2.5	2.00
2	Select Compacted Clay/Soil Barrier Layer	130	2.0	1.81
3	Waste Fill	119	220.7	182.38
4	Select Aggregate Fill	125	2.5	2.17

Note: Load is calculated by prism method

Wheeled Vehicle Inputs:

VEHICLE NO.	VEHICLE DESCRIPTION	NO. OF WHEELS	WEIGHT DISTRIBUTION	OPERATING WEIGHT (lbs)	WEIGHT PER WHEEL (lbs)
	N/A- Deep fill. Vehicle load is insignificant.				
					-

Tracked Vehicle Inputs:

VEHICLE NO.	VEHICLE TYPE	OPERATING WEIGHT PER TRACK (lbs)	TRACK WIDTH (ft)	TRACK LENGTH (ft)	WEIGHT PER TRACK (lbs)	GROUND CONTACT AREA PER TRACK (in^2)	DISTRIBUTED LOAD PER TRACK (psi)
	N/A- Deep fill. Vehicle load is insignificant.					-	-

=> For tracked vehicles the load is the largest,
thus use psi to determine PLS

Live-Loading Calculation:

Equations (PPI, 2009):

Boussinesq Equation for Point (Wheeled) Loading (PPI, 2009):

$$P_L = \frac{3\, I_z\, P\, H^3}{2\, \pi\, r^5} \qquad r = (X^2 + H^2)^{1/2}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
Iz	Road Type Impact Factor	2	unitless	For dirt roads (PPI, 2009)
P	Concentrated Surface Load	1	lbs	has the largest load
H	Depth of Soil Cover	2732.4	in	User input "Soil Inputs" table
X	Horizontal Distance of Wheel from Pipe	0	in	r = H for one wheel directly above the pipe
r	Radial Distance of Load from Pipe	2732.4	in	Wheel is directly above the pipe
PL	Vertical Pressure Acting on the Pipe	**0.00**	**psi**	Calculated Value

Area (Track) Loading Equation (PPI, 2009):

$$P_{LS} = 4\, I_V\, w_s$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
ws	Distributed Pressure of the Track	0	psi	has the largest distributed load
M	1/2 Track Width	0.0	ft	Figure 3-5 in PPI, 2009
M/H	**Ratio of Track Width to Soil Depth**	**0.000**	ft/ft	Table 1 from PPI, 2009
N	1/2 Track Length	0.0	ft	Figure 3-5 in PPI, 2009
N/H	**Ratio of Track Length to Soil Depth**	**0.000**	ft/ft	Table 1 from PPI, 2009
Iv	Influence value for distributed loads	**0.009**	unitless	**Table 1 from PPI, 2009. (manual input)**
PLS	Vertical pressure due to the track area load	**0.00**	**psi**	Calculated Value

PROJECT / PROPOSAL NAME / LOCATION: Orchard Ridge- Pipe Strength Calculations				PROJECT / PROPOSAL NO. 324442.0005.0000
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Point Load		**Area Load**	
0.00	>	0.00	psi

=> Use Area Load

Pipe Strength Reduction From Perforations

Loading Adjustment Equation for Perforations (Inverse of Pipe Strength Reduction) (Duffy, 2006):

$$P_{LV} = \frac{12 * (P_L or P_{LS})}{12 - D * N} \qquad P_E = \frac{12 * \sum[(Soil\ Layer\ Depth) * (Soil\ Layer\ Unit\ Weigh}{12 - D * N}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
D	Perforation Diameter	0.5	in	1/2" perforation
N	Number of Perforations / Foot of Pipe	6	ft	2 perforation pairs every 6 inches
P_{LV}	Modified Vertical Live Load	0.00	psi	Calculated
P_E	Modified Vertical Soil Load	251.1	psi	Calculated

Pipe Resistance Inputs:

PIPE NUMBER	PIPE TYPE	NOMINAL DIAMETER (in)	OUTSIDE DIAMETER (in)	DIMENSION RATIO, DR	MINIMUM THICKNESS (in)	AVERAGE INSIDE DIAMETER (in)
1	6 inch SDR 11 HDPE Pipe	6	6.625	11	0.602	5.349

Pipe Resistance Calculations:

Pipe Deflection

Harrison and Watkins Equations (1996)

$$D_{sidewall} = \frac{F_{max}}{M_{s,\,bedding}} \qquad \%Deflection = \frac{D_{sidewall}}{OD} \cdot 100$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION/REFERENCE
P_{max}	Maximum Pipe Loading	251.14	psi	$\sum(\gamma \cdot H)$ where H>50ft
OD	Outside Diameter	6.63	in	Pipe Manufacturer
F_{max}	Maximum Load	1663.81	lb/in	P_{max} * OD
SDR	Standard Dimension Ratio	11	in/in	Pipe Manufacturer
$M_{s,bedding}$	Bedding Constrained Modulus	6,500	psi	Gravelly sands/gravels @ 95% std. Proctor assuming a vertical soil stress of 100 psi; Table 3-12 PPI 2009
$D_{sidewall}$	Sidewall Deflection	0.26	in	calculated
X/D	**% Deflection**	3.86%	**percent**	**Calculated, Allowable Value is 7.5%**

Pipe Wall Compression (Crushing Fig 3-1B Ch 6):

Wall Compression Equations Eq 3-21, Eq 3-22, and Eq 3-23 Chapter 6 (PPI, 2009):

$$VAF = 0.88 - 0.71\frac{S_A - 1}{S_A + 2.5} \qquad S_A = \frac{1.43 M_S r_{cent}}{EA} \qquad PRD = (VAF)\text{wH}$$

$$S = \frac{(P_{RD} + P_{LV})DR}{2} < S_{allowable}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
M_s	**One Dimensional Modulus of Soil**	6,500	psi	Gravelly sands/gravels @ 95% std. Proctor assuming a vertical soil stress of 100 psi; Table 3-12 PPI 2009
r_{cent}	**Radius to the Centroidal Axis of Pipe**	3.28	in	Calculated, average inside diameter/2 + wall thickness
E	**Apparent Modulus of Elasticity of Pipe**	28000	psi	50-years, PE3XXX Table B.1.1 from PPI, 2009
A	**Profile Wall Average Cross Sectional Area**	0.602	in^2/in	wall thickness for DR pipe
S_A	**Hoop Thrust Stiffness Ratio**	1.8	-	Calculated
VAF	**Vertical Arching Factor**	0.75	-	Calculated
P_{RD}	Vertical Load from Soil Pressure	140.7	psi	Calculated
P_{LV}	Vertical Load from Vehicle	0.00	psi	Calculated
DR	Dimension Ratio (OD/t)	11	in/in	Pipe Manufacturer
S	Pipe Wall Compressive Stress	774	psi	Calculated
$S_{allowable}$	Allowable Compressive Stress	780	psi	Table C.1 (PE 3408) from PPI, 2009
	Factor of Safety	**1.01**		

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PREPARED/UPDATED BY:	J. Bell; A. Rowley; B. Kahnk	DATE:	8/12/2021; 11/10/2021; 9/28/2022	FINAL
CHECKED BY:	A. Rowley; B. Kahnk; M. Dogan	DATE:	8/12/2021; 11/10/2021; 9/28/2022	REVISION

Pipe Wall Buckling:

Luscher Equation for Constrained Buckling Below Ground Water Level Eq 3-15 Chapter 6 (PPI, 2009):

$$P_{WC} = 5.65 * \sqrt{R * B' * E' * \left(\frac{E}{12 * (DR-1)^3}\right)} \qquad B' = \frac{1}{1+4e^{-0.065H}} \qquad Factor\ of\ Safety = \frac{P_{Wc}}{P_{LV} + P_E}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
R	Buoyancy Reduction Factor	1.0	unitless	Where R = 1 -0.33 * (Height of groundwater above pipe/ depth of cover)
H	Total depth of soil load above pipe	227.7	ft	User input "Soil Inputs" table
E'	Modulus of Soil Reaction	2500	psi	ands/gravels @ 95% std. Proctor assuming a vertical soil stress of 100 psi; Table 3-1
E	Apparent Modulus of Elasticity	28000	psi	50-years, PE3XXX Table B.1.1 from PPI, 2009
DR	Dimension Ratio	11	in/in	Pipe Manufacturer
B'	Soil Support Factor	1.00	unitless	Calculated
P_{WC}	Allowable Buckling Pressure	431	psi	Calculated
	Factor of Safety	**1.7**		

Pipe Wall Buckling:

Moore-Selig Equation for Critical buckling pressure Eq 3-29 Chapter 6 (PPI, 2009):

P_{cr}= (2.4*Fo*Rh/Dm)*((EI)^.33*)*(Es'^.67)

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
DR	Dimension Ratio	11	in/in	Pipe Manufacturer
E	Apparent Modulus of Elasticity	28000	psi	PE3XXX Table B.2.1 from PPI, 2009
Ms	One Dimensional Modulus of Soil	6,500	psi	ravelly sands/gravels @ 95% std. Proctor assuming a vertical soil stress of 100 psi; Table 3-12 PPI 200
Dm	Mean diameter	6.023	in	Pipe Manufacturer
I	Pipe wall moment of inertia	0.018	in4/in	calculated; assumed solid wall construction
μ	Poisson's Ratio	0.15	unitless	Table 3-13, PPI 2009
Es'	Secant modulus of the soil	6156	psi	Calculated
F_O	Calibration Factor	0.55	unitless	granular soils
Rh	Geometry Factor	1	unitless	Assumed for deep burials
P_{CR}	A. Critical Buckling Pressure (constrained)	588	psi	Calculated
P_B	Constraining Pressure	251		
	Factor of Safety	**2.34**		**Required FS >= 2.0**

PROJECT / PROPOSAL NAME / LOCATION: Orchard Ridge- Pipe Strength Calculations				PROJECT / PROPOSAL NO. 324442.0005.0000
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PIPE STRENGTH CALCULATIONS
64.4 FT DEEP FILL
LONG-TERM LOADING

Live-Loading Inputs:

Soil Inputs:

SOIL LAYER	SOIL TYPE	UNIT WEIGHT (pcf)	SOIL LAYER THICKNESS (ft)	SOIL LAYER LOAD (psi)
1	Rooting zone/topsoil	115	2.5	2.00
2	Select Compacted Clay/Soil Barrier Layer	130	2.0	1.81
3	Waste Fill	119	56.9	47.02
4	Select Aggregate Fill	125	3.0	2.60

Note: Load is calculated by prism method

Wheeled Vehicle Inputs:

VEHICLE NO.	VEHICLE DESCRIPTION	NO. OF WHEELS	WEIGHT DISTRIBUTION	OPERATING WEIGHT (lbs)	WEIGHT PER WHEEL (lbs)
	N/A- Deep fill. Vehicle load is insignificant.				
					-

Tracked Vehicle Inputs:

VEHICLE NO.	VEHICLE TYPE	OPERATING WEIGHT PER TRACK (lbs)	TRACK WIDTH (ft)	TRACK LENGTH (ft)	WEIGHT PER TRACK (lbs)	GROUND CONTACT AREA PER TRACK (in^2)	DISTRIBUTED LOAD PER TRACK (psi)
	N/A- Deep fill. Vehicle load is insignificant.					-	-

=> For tracked vehicles the load is the largest,
thus use psi to determine PLS

Live-Loading Calculation:

Equations (PPI, 2009):

Boussinesq Equation for Point (Wheeled) Loading (PPI, 2009):

$$P_L = \frac{3\, I_z\, P\, H^3}{2\, \pi\, r^5} \qquad r = (X^2 + H^2)^{1/2}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
Iz	Road Type Impact Factor	2	unitless	For dirt roads (PPI, 2009)
P	Concentrated Surface Load	1	lbs	has the largest load
H	Depth of Soil Cover	772.8	in	User input "Soil Inputs" table
X	Horizontal Distance of Wheel from Pipe	0	in	r = H for one wheel directly above the pipe
r	Radial Distance of Load from Pipe	772.8	in	Wheel is directly above the pipe
PL	Vertical Pressure Acting on the Pipe	**0.00**	**psi**	Calculated Value

Area (Track) Loading Equation (PPI, 2009):

$$P_{LS} = 4\, I_V\, w_s$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
ws	Distributed Pressure of the Track	0	psi	has the largest distributed load
M	1/2 Track Width	0.0	ft	Figure 3-5 in PPI, 2009
M/H	**Ratio of Track Width to Soil Depth**	**0.000**	ft/ft	Table 1 from PPI, 2009
N	1/2 Track Length	0.0	ft	Figure 3-5 in PPI, 2009
N/H	**Ratio of Track Length to Soil Depth**	**0.000**	ft/ft	Table 1 from PPI, 2009
Iv	Influence value for distributed loads	**0.009**	unitless	**Table 1 from PPI, 2009. (manual input)**
PLS	Vertical pressure due to the track area load	**0.00**	**psi**	Calculated Value

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Point Load		Area Load	
0.00	>	0.00	psi

=> Use Area Load

Pipe Strength Reduction From Perforations

Loading Adjustment Equation for Perforations (Inverse of Pipe Strength Reduction) (Duffy, 2006):

$$P_{LV} = \frac{12 * (P_L or P_{LS})}{12 - D * N} \qquad P_E = \frac{12 * \sum[(Soil\ Layer\ Depth) * (Soil\ Layer\ Unit\ Weigh}{12 - D * N}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
D	Perforation Diameter	0.5	in	1/2" perforation
N	Number of Perforations / Foot of Pipe	12	ft	4 perforation sets every 6 inches
P_{LV}	Modified Vertical Live Load	0.00	psi	Calculated
P_E	Modified Vertical Soil Load	106.9	psi	Calculated

Pipe Resistance Inputs:

PIPE NUMBER	PIPE TYPE	NOMINAL DIAMETER (in)	OUTSIDE DIAMETER (in)	DIMENSION RATIO, DR	MINIMUM THICKNESS (in)	AVERAGE INSIDE DIAMETER (in)
1	18 inch SDR 11 HDPE Pipe	18	18	11	1.636	14.532

Pipe Resistance Calculations:

Pipe Wall Deflection:

Modified Iowa Equation Eq 3-10 Chapter 6 (PPI, 2009):

$$\%\frac{X}{D} = \left(\frac{K_{BED}L_{DL}P_E + K_{BED}P_{LV}}{\left(\frac{2E}{3}\right)\left(\frac{1}{(DR-1)^3}\right) + 0.061F_S E'}\right)$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
K_{BED}	Bedding Factor	0.1	unitless	Typical value
L_{DL}	Deflection Lag Factor	1	unitless	If soil pressure calculated by prism method use 1.0 (Ch6 p216, PPI 2009), Watkins '96
P_E	Vertical Load from Soil Pressure	106.9	psi	Calculated
P_{LV}	Vertical Load from Vehicle	0.00	psi	Calculated
E	Apparent Modulus of Elastic Pipe	28000	psi	50-years, PE3XXX Table B.1.1 from PPI, 2009
E'	Modulus of Soil Reaction	2500	psi	Crushed rock. From Table 3-8 PPI, 2009
F_S	Soil Support Factor	1	unitless	Table 3-10 (trench width>>OD of pipe) from PPI, 2009
DR	Dimension Ratio (OD/t)	11	in/in	Pipe Manufacturer
X/D	**% Deflection**	**6%**	**percent**	**Calculated, Allowable Value is 7.5%**

Pipe Wall Compression (Crushing Fig 3-1B Ch 6):

Wall Compression Equation Eq 3-13 Chapter 6 (PPI, 2009):

$$S = \frac{(P_E + P_{LV})DR}{2} < S_{allowable}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
P_E	Vertical Load from Soil Pressure	106.9	psi	Calculated
P_{LV}	Vertical Load from Vehicle	0.00	psi	Calculated
DR	Dimension Ratio (OD/t)	11	in/in	Pipe Manufacturer
S	Pipe Wall Compressive Stress	588	psi	Calculated
$S_{allowable}$	Allowable Compressive Stress	780	psi	Table C.1 (PE 3408) from PPI, 2009
	Factor of Safety	**1.33**		

PROJECT / PROPOSAL NAME / LOCATION: Orchard Ridge- Pipe Strength Calculations				PROJECT / PROPOSAL NO. 324442.0005.0000
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Pipe Wall Buckling:

Luscher Equation for Constrained Buckling Below Ground Water Level Eq 3-15 Chapter 6 (PPI, 2009):

$$P_{WC} = 5.65 * \sqrt{R * B' * E' * \left(\frac{E}{12 * (DR-1)^3}\right)} \qquad B' = \frac{1}{1 + 4e^{-0.065H}} \qquad Factor\ of\ Safety = \frac{P_{Wc}}{P_{LV} + P_E}$$

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
R	Buoyancy Reduction Factor	0.868	unitless	Where R = 1 -0.33 * (Height of groundwater above pipe/ depth of cover)
H	Total depth of soil load above pipe	64.4	ft	User input "Soil Inputs" table
E'	Modulus of Soil Reaction	2500	psi	Crushed rock. From Table 3-8 PPI, 2009
E	Apparent Modulus of Elasticity	28000	psi	50-years, PE3XXX Table B.1.1 from PPI, 2009
DR	Dimension Ratio	11	in/in	Pipe Manufacturer
B'	Soil Support Factor	0.94	unitless	Calculated
P_{WC}	Allowable Buckling Pressure	390	psi	Calculated
	Factor of Safety	**3.7**		

Pipe Wall Buckling:

PVC manual page 7.38 EQ 7.18 for Constrained Buckling in dry soil above groundwater level

Pcr= 2*Fo*E/ { [1-nu^2][DR-1]^3}

Pb = 1.15 Sqrt[Pcr E']

PARAMETER	DESCRIPTION	VALUE	UNITS	ASSUMPTION / REFERENCE
DR	Dimension Ratio	11	in/in	Pipe Manufacturer
E	Apparent Modulus of Elasticity	28000	psi	PE3XXX Table B.2.1 from PPI, 2009
E'	Modulus of Soil Reaction	2500	psi	Crushed rock. From Table 3-8 PPI, 2009
D_I	Average Inside Diameter	14.532	in	Pipe Manufacturer
D_{Min}	Minimum Inside Diameter		in	Pipe Manufacturer
%Delection	Percent Deflection		percent	(D_I - D_MIN) / D_I
μ	Poisson's Ratio	0.45	unitless	Chapter 3, Appendix D from PPI, 2009
F_O	Ovality Correction Factor	0.8	unitless	Determined from Figure 3-9 from PPI, 2009
P_{CR}	A. Critical Buckling Pressure (unconstrained)	56	psi	Calculated
P_B	Allowable Buckling Pressure	431		
	Unconstrained Factor of Safety	0.53		
	Factor of Safety	**4.03**		**Required FS >= 2.0**

Reference Sheets

- Boussinesq's Formula
- Watkins Method
- Buckling
- Deep Fill Installation
- Pipe Properties

Boussinesq’s Formula

Boussinesq Equation

The Boussinesq Equation gives the pressure at any point in a soil mass under a concentrated surface load. The Boussinesq Equation may be used to find the pressure transmitted from a wheel load to a point that is not along the line of action of the load. Pavement effects are neglected.

(3-4)

$$P_L = \frac{3 \quad {}_{f} \qquad {}^{3}}{2\pi\, r^5}$$

WHERE

P_L = vertical soil pressure due to live load lb/ft^2

= wheel load, lb

= vertical depth to pipe crown, ft

f = impact factor

r = distance from the point of load application to pipe crown, ft

(3-5)

$$r = \sqrt{\quad {}^{2} + \quad {}^{2}}$$

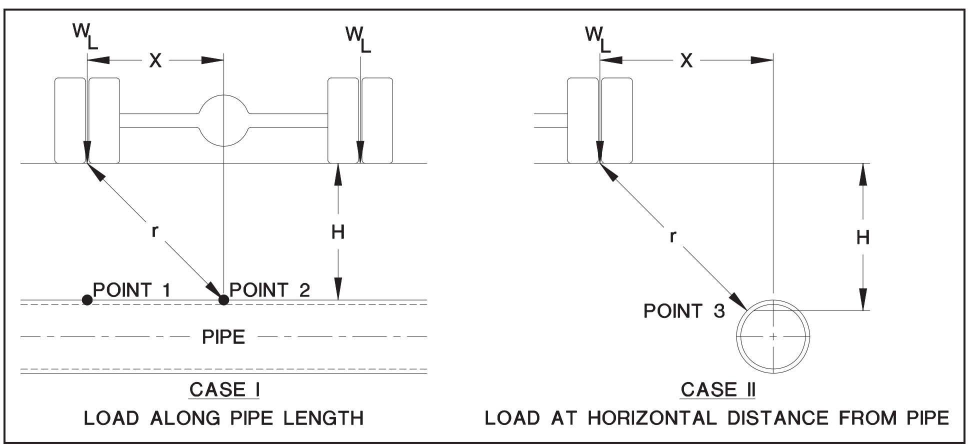


Figure 3-4 Illustration of Boussinesq Point Loading

Example Using Boussinesq Point Loading Technique

Determine the vertical soil pressure applied to a 12" pipe located 4 ft deep under a dirt road when two vehicles traveling over the pipe and in opposite lanes pass each other. Assume center lines of wheel loads are at a distance of 4 feet. Assume a wheel load of 16,000 lb.

Watkins Method

Compare this with the constrained buckling pressure. Since P_{WC} exceeds P_E, DR 26 has satisfactory resistance to constrained pipe buckling.

Installation Category #2: Shallow Cover Vehicular Loading

The Standard Installation methodology assumes that the pipe behaves primarily as a "membrane" structure, that is, the pipe is almost perfectly flexible with little ability to resist bending. At shallow cover depths, especially those less than one pipe diameter, membrane action may not fully develop, and surcharge or live loads place a bending load on the pipe crown. In this case the pipe's flexural stiffness carries part of the load and prevents the pipe crown from dimpling inward under the load. Equation 3-19, published by Watkins [14] gives the soil pressure that can be supported at the pipe crown by the combination of the pipe's flexural stiffness (bending resistance) and the soil's internal resistance against heaving upward. In addition to checking Watkins' formula, the designer should check deflection using Equations 3-10 or 3-11, pipe wall compressive stress using Equations 3-13 or 3-14, and pipe wall buckling using Equations 3-15 or 3-16.

Watkins' equation is recommended only where the depth of cover is greater than one-half of the pipe diameter and the pipe is installed at least 18 inches below the road surface. In other words, it is recommended that the pipe regardless of diameter always be at least 18" beneath the road surface where there are live loads present; more may be required depending on the properties of the pipe and installation. In some cases, lesser cover depths may be sufficient where there is a reinforced concrete cap or a reinforced concrete pavement slab over the pipe. Equation 3-19 may be used for both DR pipe and profile pipe. See definition of "A" below.

(3-19)

$$P_{WAT} = \frac{12w(KH)^2}{N_S D_O} + \frac{7387(I)}{N_S D_O^2 c}\left(S_{MAT} - \frac{w D_O H}{288A}\right)$$

WHERE

P_{WAT} = allowable live load pressure at pipe crown for pipes with one diameter or less of cover, psf

w = unit weight of soil, lb/ft^3

D_O = pipe outside diameter, in

H = depth of cover, ft

I = pipe wall moment of inertia ($t^3/12$ for DR pipe), in^4/in

A = profile wall average cross-sectional area, in^2/in, for profile pipe or wall thickness (in) for DR pipe (obtain the profile from the manufacturer of the profile pipe.)

c = outer fiber to wall centroid, in

c = H_P – z for profile pipe and c = 0.5t for DR pipe, in

H_P = profile wall height, in

z = pipe wall centroid, in

S_{MAT} = material yield strength, lb/in^2, Use 3000 PSI for PE3408

N_S = **safety factor**

K = **passive earth pressure coefficient**

(3-20)

$$K = \frac{1 + \mathrm{SIN}(\phi)}{1 - \mathrm{SIN}(\phi)}$$

ϕ = **angle of internal friction, deg**

Equation 3-19 is for a point load applied to the pipe crown. Wheel loads should be determined using a point load method such as given by Equations 3-2 (Timoshenko) or 3-4 (Boussinesq).

When a pipe is installed with shallow cover below an unpaved surface, rutting can occur which will not only reduce cover depth, but also increase the impact factor.

Shallow Cover Example

Determine the safety factor against flexural failure of the pipe accompanied by soil heave, for a 36" RSC 100 F894 profile pipe 3.0 feet beneath an H20 wheel load. Assume an asphalt surface with granular embedment.

SOLUTION: The live load pressure acting at the crown of the pipe can be found using Equation 3-4, the Boussinesq point load equation. At 3.0 feet of cover the highest live load pressure occurs directly under a single wheel and equals:

$$P_L = \frac{(3)(2.0)(6000)(3.0)^3}{2\pi(3.0)^5} = 1697 \ psf$$

WHERE

I_f = **2.0**

W = **16,000 lbs**

H = **3.0 ft**

w = **120 pcf**

The live load pressure is to be compared with the value in Equation 3-19. To solve Equation 3-19, the following parameters are required:

I = **0.171 in^4/in**

A = **0.470 in^2/in**

H_P = **2.02 in (Profile Wall Height)**

D_O = **D_I+2*h = 36.00+2*2.02 = 40.04 in**

Z = **0.58 in**

C = **h-z = 1.44 in**

S = **3000 psi**

ϕ = **30 deg.**

Buckling

raised to a power. Therefore the lower the DR, the higher the resistance. Buried pipe has an added resistance due to support (or constraint) from the surrounding soil.

Non-pressurized pipes or gravity flow pipes are most likely to have a net compressive stress in the pipe wall and, therefore, the allowable buckling pressure should be calculated and compared to the total (soil and ground water) pressure. For most pressure pipe applications, the fluid pressure in the pipe exceeds the external pressure, and the net stress in the pipe wall is tensile. Buckling needs only be considered for that time the pipe is not under pressure, such as during and immediately after construction and during system shut-downs and, in cases in which a surge pressure event can produce a temporary negative internal pressure. Under these circumstances the pipe will react much stiffer to buckling as its modulus is higher under short term loading. When designing, select a modulus appropriate for the duration of the negative external pressure. For pipe that are subjected to negative pressure due to surge, consideration should be given to selecting a DR that gives the pipe sufficient unconstrained collapse strength to resist the full applied negative pressure without support for the soil. This is to insure against construction affects that result in the embedment material not developing its full design strength.

This chapter gives two equations for calculating buckling. The modified Luscher Equation is for buried pipes that are beneath the ground water level, subject to vacuum pressure, or under live load with a shallow cover. These forces act to increase even the slightest eccentricity in the pipe wall by following deformation inward. While soil pressure alone can create instability, soil is less likely to follow deformation inward, particularly if it is granular. So, dry ground buckling is only considered for deep applications and is given by the Moore-Selig Equation found in the section, “Buckling of Pipes in Deep, Dry Fills”.

Luscher Equation for Constrained Buckling Below Ground Water Level

For pipes below the ground water level, operating under a full or partial vacuum, or subject to live load, Luscher’s equation may be used to determine the allowable constrained buckling pressure. Equation 3-15 and 3-16 are for DR and profile pipe respectively.

(3-15)

$$P_{WC} = \frac{5.65}{N}\sqrt{RB'E'\frac{E}{12(DR-1)^3}}$$

(3-16)

$$P_{WC} = \frac{5.65}{N}\sqrt{RB'E'\frac{EI}{D_M^{\,3}}}$$

WHERE

P_{WC} = allowable constrained buckling pressure, lb/in^2

N = safety factor

(3-17)

$$R = \quad .33 \frac{W}{}$$

WHERE

R = buoyancy reduction factor

W = height of ground water above pipe, ft

= depth of cover, ft

(3-18)

$$B' = \frac{}{\quad . \; 65}$$

WHERE

= natural log base number, 2.71828

E = soil reaction modulus, psi

E = apparent modulus of elasticity, psi

DR = Dimension Ratio

I = pipe wall moment of inertia, in^4/in (t^3/12, if solid wall construction)

D_M = Mean diameter (D_I + 2z or D_O – t), in

Although buckling occurs rapidly, long-term external pressure can gradually deform the pipe to the point of instability. This behavior is considered viscoelastic and can be accounted for in Equations 3-15 and 3-16 by using the apparent modulus of elasticity value for the appropriate time and temperature of the loading. For instance, a vacuum event is resisted by the short-term value of the modulus whereas continuous ground water pressure would be resisted by the 50 year value. For modulus values see Appendix, Chapter 3.

For pipes buried with less than 4 ft or a full diameter of cover, Equations 3-15 and 3-16 may have limited applicability. In this case the designer may want to use Equations 3-39 and 3-40.

The designer should apply a safety factor commensurate with the application. A safety factor of 2.0 has been used for thermoplastic pipe.

The allowable constrained buckling pressure should be compared to the total vertical stress acting on the pipe crown from the combined load of soil, and ground water or floodwater. It is prudent to check buckling resistance against a ground water level for a 100-year-flood. In this calculation the total vertical stress is typically taken as the prism load pressure for saturated soil, plus the fluid pressure of any floodwater above the ground surface.

For DR pipes operating under a vacuum, it is customary to use Equation 3-15 to check the combined pressure from soil, ground water, and vacuum, and then to use the unconstrained buckling equation, Equation 3-39, to verify that the pipe can operate with the vacuum independent of any soil support or soil load, in case construction does not develop the full soil support. Where vacuum load is short-term, such as during water hammer events two calculations with Equation 3-14 are necessary. First determine if the pipe is sufficient for the ground water and soil pressure using a long-term modulus; then determine if the pipe is sufficient for the combined ground water, soil pressure and vacuum loading using the short-term modulus.

Constrained Buckling Example

Does a 36" SDR 26 PE4710 pipe have satisfactory resistance to constrained buckling when installed with 18 ft of cover in a compacted soil embedment? Assume ground water to the surface and an E' of 1500 lb/in^2.

SOLUTION: Solve Equation 3-15. Since this is a long-term loading condition, the 50 year stress relaxation modulus for PE4710 material is given in the Appendix to Chapter 3 as 29,000 psi. Soil cover, H, and ground water height, H_{GW}, are both 18 feet. Therefore, the soil support factor, B', is found as follows;

$$B' = \frac{}{.\ 65} = \ .\ \ 6$$

and the bouyancy reduction factor, R, is found as follows:

$$R = \ \ .33 \text{—} = \ .6$$

Solve Equation 3-15 for the allowable long-term constrained buckling pressure:

$$P_{WC} = \frac{5.65}{} \sqrt{\frac{.6 \quad . \quad 6\ 15}{12(26-1)^3}}$$

$$P_{WC} = 23.5 \qquad = 3387$$

The earth pressure and ground water pressure applied to the pipe is found using Equation 3-1 (prism load) with a saturated soil weight. The saturated soil weight being the net weight of both soil and water.

$$P_E = \qquad = \ 6 \ \text{—}$$

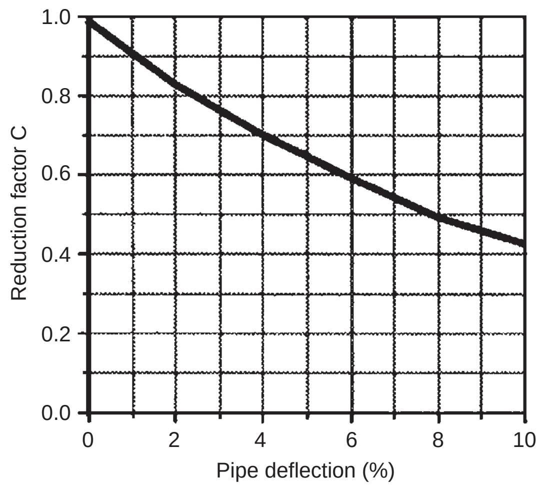


Fig. 7.16 Critical buckling pressure reduction factor C for shape.

According to Janson, when pipes are buried or installed in a way that allows soil or surrounding medium to provide some resistance against buckling or deflection, the buckling pressure (P_b) in the soil is found to be:

Equation 7.18

$$P_b = 1.15\sqrt{P_{cr}E'}$$

where:

P_b = buckling pressure in a given soil, psi
E' = modulus of soil reaction, psi

Example 7.3

If a DR 35 PVC sewer pipe with a 400,000 psi modulus of elasticity is confined in a saturated soil providing $E' = 800$ psi, what height (H) of the saturated soil with density 120 lb/ft^3 (w) would cause buckling? What maximum cover height ensures that deflection $\%\Delta Y/D$ does not exceed 7.5%? Assume bedding angle of zero ($K = 0.11$).

Solution

Find first the critical buckling pressure, using Equation 7.14:

$$P_{cr} = \frac{2E}{(1-\nu^2)(DR-1)^3} = \frac{2(400{,}000)}{[1-(0.38)^2](35-1)^3} = 23.8 \text{ psi}$$

Then, determine the buckling pressure in this soil:

$$P_b = 1.15\sqrt{(23.8)(800)} = 158.7 \text{ psi} = 22{,}850 \text{ lb/ft}^2$$

This is, then, the prism load (P_v), which is used to find maximum cover height H:

$$H = P_v/w = 22{,}850/120 = 190 \text{ ft}$$

where:

H = height of fill above top of pipe, ft
P_v = vertical soil pressure due to the prism load, lb/ft^2

To limit deflection %ΔY/D to 7.5%, maximum cover height (H) is found via prism load pressure (i.e., pressure of vertical column of soil) using Eq 7.9 with W′ = 0:

$$w = \text{Soil unit weight, lb/ft}^3$$

$$\%\Delta Y/D = \frac{KP_v(100)}{0.149\,PS + 0.061E'}$$

$$P_v = \frac{\%\Delta Y/D(0.149\,PS + 0.061E')}{100K} = \frac{7.5[(0.149)(46) + (0.61)(800)]}{(100)(0.11)}$$

$$= 37.9 \text{ psi} = 5{,}464 \text{ lb/ft}^2$$

Thus,

$$H \text{ (to limit deflection)} = 5{,}464/120 = 45.5 \text{ ft}$$

Maximum cover is limited by the allowable deflection, not by buckling. Therefore, the safety factor for the critical failure mode by buckling of DR 35 PVC pipe is ample.

7.8.7 Localized Profile Buckling Performance Limit

Localized profile buckling is known to be a design-limiting issue for some thermoplastic pipes. Evaluations of profile PVC pipe have shown that localized buckling is not a factor.

7.8.8 Wall-Crushing Performance Limit

Research has established that flexible steel pipe walls can buckle at deflections considerably less than 20% if load is large and the soil surrounding the pipe is extremely compacted. Based on these observations, H. L. White and J. P. Layer proposed the *ring compression*

Deep Fill Installation

Installation Category #3: Deep Fill Installation

The performance limits for pipes in a deep fill are the same as for any buried pipe. They include:

1. Compressive ring thrust stress
2. Ring deflection
3. Constrained pipe wall buckling

The suggested calculation method for pipe in deep fill applications involves the introduction of design routines for each performance limit that are different than those previously given.

Compressive ring thrust is calculated using soil arching. The arching calculation may also be used for profile pipe designs in standard trench applications. Profile pipes are relatively low stiffness pipes where significant arching may occur at relatively shallow depths of cover.

At a depth of around 50 feet or so it becomes impractical to use Spangler's equation as published in this chapter because it neglects the significant load reduction due to arching and the inherent stiffening of the embedment and consequential increase in E' due to the increased lateral earth pressure applied to the embedment. This section gives an alternate deflection equation for use with PE pipes. It was first introduced by Watkins et al. [(1)] for metal pipes, but later Gaube extended its use to include PE pipes. [(15)]

Where deep fill applications are in dry soil, Luscher's equation (Eq. 3-15 or 3-16) may often be too conservative for design as it considers a radial driving force from ground water or vacuum. Moore and Selig[17] developed a constrained pipe wall buckling equation suitable for pipes in dry soils, which is given in a following section.

Considerable care should be taken in the design of deeply buried pipes whose failure may cause slope failure in earthen structures, or refuse piles or whose failure may have severe environmental or economical impact. These cases normally justify the use of methods beyond those given in this Chapter, including finite element analysis and field testing, along with considerable professional design review.

Compressive Ring Thrust and the Vertical Arching Factor

The combined horizontal and vertical earth load acting on a buried pipe creates a radially-directed compressive load acting around the pipe's circumference. When a PE pipe is subjected to ring compression, thrust stress develops around the pipe hoop, and the pipe's circumference will ever so slightly shorten. The shortening permits "thrust arching," that is, the pipe hoop thrust stiffness is less than the soil hoop thrust stiffness and, as the pipe deforms, less load follows the pipe. This occurs much like the vertical arching described by Marston.[18] Viscoelasticity enhances this effect. McGrath[19] has shown thrust arching to be the predominant form of arching with PE pipes.

Burns and Richard[6] have published equations that give the resulting stress occurring in a pipe due to arching. As discussed above, the arching is usually considered when calculating the ring compressive stress in profile pipes. For deeply buried pipes McGrath [19] has simplified the Burns and Richard's equations to derive a vertical arching factor as given by Equation 3-21.

(3-21)

$$VAF = 0.88 - 0.71 \frac{S_A - 1}{S_A + 2.5}$$

WHERE

VAF **= Vertical Arching Factor**

S_A **= Hoop Thrust Stiffness Ratio**

(3-22)

$$S_A = \frac{1.43\, M_S\, r_{CENT}}{EA}$$

WHERE

r_{CENT} **= radius to centroidal axis of pipe, in**

M_S**= one-dimensional modulus of soil, psi**

E **= apparent modulus of elasticity of pipe material, psi (See Appendix, Chapter 3)**

A**= profile wall average cross-sectional area, in^2/in, or wall thickness (in) for DR pipe**

One-dimensional modulus values for soil can be obtained from soil testing, geotechnical texts, or Table 3-12 which gives typical values. The typical values in Table 3-12 were obtained by converting values from McGrath [20].

TABLE 3-12
Typical Values of M_S, One-Dimensional Modulus of Soil

Vertical Soil Stress[1] (psi)	Gravelly Sand/Gravels 95% Std. Proctor (psi)	Gravelly Sand/Gravels 90% Std. Proctor (psi)	Gravelly Sand/Gravels 85% Std. Proctor (psi)
10	3000	1600	550
20	3500	1800	650
40	4200	2100	800
60	5000	2500	1000
80	6000	2900	1300
100	6500	3200	1450

* Adapted and extended from values given by McGrath[20]. For depths not shown in McGrath[20], the MS values were approximated using the hyperbolic soil model with appropriate values for K and n where n=0.4 and K=200, K=100, and K=45 for 95% Proctor, 90% Proctor, and 85% Proctor, respectively.

[1] Vertical Soil Stress (psi) = [soil depth (ft) x soil density (pcf)]/144

The radial directed earth pressure can be found by multiplying the prism load (pressure) by the vertical arching factor as shown in Eq. 3-23.

(3-23) $$P_{RD} = (VAF)wH$$

WHERE

P_{RD} **= radial directed earth pressure, lb/ft²**

w **= unit weight of soil, pcf**

H **= depth of cover, ft**

The ring compressive stress in the pipe wall can be found by substituting P_{RD} from Equation 3-23 for P_E in Equation 3-13 for DR pipe and Equation 3-14 for profile wall pipe.

Earth Pressure Example

Determine the earth pressure acting on a 36" profile wall pipe buried 30 feet deep. The following properties are for one unique 36" profile pipe made from PE3608 material. Other 36" profile pipe may have different properties. The pipe's cross-sectional area, A, equals 0.470 inches²/inch, its radius to the centroidal axis is 18.00 inches plus 0.58 inches, and its apparent modulus is 27,000 psi. Its wall height is 2.02 in and its D_O equals 36 in +2 (2.02 in) or 40.04 in. Assume the pipe is installed in a clean granular soil compacted to 90% Standard Proctor (Ms = 1875 psi), the insitu soil is as stiff as the embedment, and the backfill weighs 120 pcf. (Where the excavation is in a stable trench, the stiffness of the insitu soil can generally be ignored in this calculation.) The following series of equations calculates the hoop compressive stress, S, in the pipe wall due to the earth pressure applied by the soil above the pipe. The earth pressure is reduced from the prism load by the vertical arching factor.

(From Equation 3-22)

$$S_A = \frac{1.43(1875\frac{lbs}{inch^2})(18.58\,inch)}{(28250\frac{lbs}{inch^2})(0.470\frac{inch^2}{inch})} = 3.93$$

(From Equation 3-21)

$$VAF = 0.88 - 0.71\frac{3.75-1}{3.75+2.5} = 0.56$$

(From Equation 3-23)

$$P_{RD} = 0.57(120\ pcf)(30\ ft) = 2016\frac{lb}{ft^2}$$

(From Equation 3-14)

$$S = \frac{P_{RD}D_O}{288A} = \frac{2052\ psf\,(40.04\,in)}{288\,(0.470\,in^2/in)} = 596\ psi \leq 1000\,psi$$

(Allowable compressive stress per Table C.1, Appendix to Chapter 3)

The secant modulus of the soil may be obtained from testing or from a geotechnical engineer's evaluation. In lieu of a precise determination, the soil modulus may be related to the one-dimensional modulus, M_S, from Table 3-12 by the following equation where μ is the soil's Poisson ratio.

(3-26)

$$E_S = M_S \frac{(1+\mu)(1-2\mu)}{(1-\mu)}$$

TABLE 3-13
Typical range of Poisson's Ratio for Soil (Bowles [21])

Soil Type	Poisson's Ratio, μ
Saturated Clay	0.4-0.5
Unsaturated Clay	0.1-0.3
Sandy Clay	0.2-0.3
Silt	0.3-0.35
Sand (Dense)	0.2-0.4
Coarse Sand (Void Ratio 0.4-0.7)	0.15
Fine-grained Sand (Void Ratio 0.4-0.7)	0.25

Moore-Selig Equation for Constrained Buckling in Dry Ground

As discussed previously, a compressive thrust stress exists in buried pipe. When this thrust stress approaches a critical value, the pipe can experience a local instability or large deformation and collapse. In an earlier section of this chapter, Luscher's equation was given for constrained buckling under ground water. Moore and Selig[17] have used an alternate approach called the continuum theory to develop design equations for contrained buckling due to soil pressure (buckling of embedded pipes). The particular version of their equations given below is more appropriate for dry applications than Luscher's equation. Where ground water is present, Luscher's equation should be used.

The Moore-Selig Equation for critical buckling pressure follows: (Critical buckling pressure is the pressure at which buckling will occur. A safety factor should be provided.)

(3-29)
$$P_{CR} = \frac{2.4\,\varphi\, R_H}{D_M}(EI)^{\frac{1}{3}}(E_S^*)^{\frac{2}{3}}$$

WHERE

P_{CR} = **Critical constrained buckling pressure, psi**

φ = **Calibration Factor, 0.55 for granular soils**

R_H = **Geometry Factor**

E = **Apparent modulus of elasticity of pipe material, psi**

I = **Pipe wall moment of Inertia, in^4/in ($t^3/12$, if solid wall construction)**

E_S^* = **E_S /(1-μ)**

E_S = **Secant modulus of the soil, psi**

μ_S = **Poisson's Ratio of Soil (Consult a textbook on soil for values. Bowles (1982) gives typical values for sand and rock ranging from 0.1 to 0.4.)**

The geometry factor is dependent on the depth of burial and the relative stiffness between the embedment soil and the insitu soil. Moore has shown that for deep burials in uniform fills, R_H equals 1.0.

Critical Buckling Example

Determine the critical buckling pressure and safety factor against buckling for the 6″ SDR 11 pipe (5.987″ mean diameter) in the previous example.

SOLUTION:

$$E_S^* = \frac{2000}{(1-0.3)} = 2860 \frac{lbs}{inch^2}$$

$$P_{CR} = \frac{2.4*0.55*1.0}{5.987}(29000*0.018)^{\frac{1}{3}}(2860)^{\frac{2}{3}} = 358 \frac{lbs}{in^2}$$

Determine the Safety Factor against buckling:

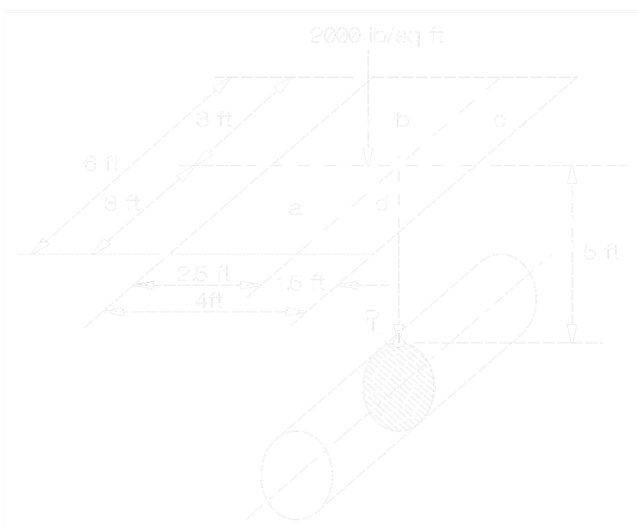
$$S.F. = \frac{P_{CR}}{P_E} = \frac{358*144}{140*75} = 4.9$$

Pipe Properties

Table 1

	N/H													
M/H	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.2**	**1.5**	**2.0**	∞
0.1	0.005	0.009	0.013	0.017	0.020	0.022	0.024	0.026	0.027	0.028	0.029	0.030	0.031	0.032
0.2	0.009	0.018	0.026	0.033	0.039	0.043	0.047	0.050	0.053	0.055	0.057	0.060	0.061	0.062
0.3	0.013	0.026	0.037	0.047	0.056	0.063	0.069	0.073	0.077	0.079	0.083	0.086	0.089	0.090
0.4	0.017	0.033	0.047	0.060	0.071	0.080	0.087	0.093	0.098	0.101	0.106	0.110	0.113	0.115
0.5	0.020	0.039	0.056	0.071	0.084	0.095	0.103	0.110	0.116	0.120	0.126	0.131	0.135	0.137
0.6	0.022	0.043	0.063	0.080	0.095	0.107	0.117	0.125	0.131	0.136	0.143	0.149	0.153	0.156
0.7	0.024	0.047	0.069	0.087	0.103	0.117	0.128	0.137	0.144	0.149	0.157	0.164	0.169	0.172
0.8	0.026	0.050	0.073	0.093	0.110	0.125	0.137	0.146	0.154	0.160	0.168	0.176	0.181	0.185
0.9	0.027	0.053	0.077	0.098	0.116	0.131	0.144	0.154	0.162	0.168	0.178	0.186	0.192	0.196
1.0	0.028	0.055	0.079	0.101	0.120	0.136	0.149	0.160	0.168	0.175	0.185	0.194	0.200	0.205
1.2	0.029	0.057	0.083	0.106	0.126	0.143	0.157	0.168	0.178	0.185	0.196	0.205	0.209	0.212
1.5	0.030	0.060	0.086	0.110	0.131	0.149	0.164	0.176	0.186	0.194	0.205	0.211	0.216	0.223
2.0	0.031	0.061	0.088	0.113	0.135	0.153	0.169	0.181	0.192	0.200	0.209	0.216	0.232	0.240
∞	0.032	0.062	0.089	0.116	0.137	0.156	0.172	0.185	0.196	0.205	0.212	0.223	0.240	0.250

* H, M, and N are per Figure 3-5.



Appendix B
Apparent Elastic Modulus

B.1 – Apparent Elastic Modulus for the Condition of Either a Sustained Constant Load or a Sustained Constant Deformation

B.1.1 – Design Values for the Base Temperature of 73°F (23°C)

TABLE B.1.1
Apparent Elastic Modulus for 73°F (23°C)

Duration of Sustained Loading	Design Values For 73°F (23°C) [1,2,3]					
	PE 2XXX		PE3XXX		PE4XXX	
	psi	MPa	psi	MPa	psi	MPa
0.5hr	62,000	428	78,000	538	82,000	565
1hr	59,000	407	74,000	510	78,000	538
2hr	57,000	393	71,000	490	74,000	510
10hr	50,000	345	62,000	428	65,000	448
12hr	48,000	331	60,000	414	63,000	434
24hr	46,000	317	57,000	393	60,000	414
100hr	42,000	290	52,000	359	55,000	379
1,000hr	35,000	241	44,000	303	46,000	317
1 year	30,000	207	38,000	262	40,000	276
10 years	26,000	179	32,000	221	34,000	234
50 years	22,000	152	28,000	193	29,000	200
100 years	21,000	145	27,000	186	28,000	193

(1) Although there are various factors that determine the exact apparent modulus response of a PE, a major factor is its ratio of crystalline to amorphous content – a parameter that is reflected by a PE's density. Hence, the major headings PE2XXX, PE3XXX and, PE4XXX, which are based on PE's Standard Designation Code. The first numeral of this code denotes the PE's density category in accordance with ASTM D3350 (An explanation of this code is presented in Chapter 5).

(2) The values in this table are applicable to both the condition of sustained and constant loading (under which the resultant strain increases with increased duration of loading) and that of constant strain (under which an initially generated stress gradually relaxes with increased time).

(3) The design values in this table are based on results obtained under uni-axial loading, such as occurs in a test bar that is being subjected to a pulling load. When a PE is subjected to multi-axial stressing its strain response is inhibited, which results in a somewhat higher apparent modulus. For example, the apparent modulus of a PE pipe that is subjected to internal hydrostatic pressure – a condition that induces bi-axial stressing – is about 25% greater than that reported by this table. Thus, the Uni-axial condition represents a conservative estimate of the value that is achieved in most applications.

It should also be kept in mind that these values are for the condition of continually sustained loading. If there is an interruption or a decrease in the loading this, effectively, results in a somewhat larger modulus.

In addition, the values in this table apply to a stress intensity ranging up to about 400psi, a value that is seldom exceeded under normal service conditions.

B.2 – Approximate Values for the Condition of a Rapidly Increasing Stress OR Strain

B.2.1 – Values for the Base Temperature of 73°F (23°C)

TABLE B.2.1

Rate of Increasing Stress	Approximate Values of Apparent Modulus for 73°F (23°C)					
	For Materials Coded PE2XXX (1)		For Materials Coded PE3XXX (1)		For Materials Coded PE4XXX (1)	
	psi	MPa	psi	MPa	psi	MPa
"Short term" (Results Obtained Under Tensile Testing) (2)	100,000	690	125,000	862	130,000	896
"Dynamic" (3)	150,000psi (1,034MPa), For All Designation Codes					

(1) See Chapter 5 for an explanation of the PE Pipe Material Designation Code. The X's designate any numeral that is recognized under this code.

(2) Under ASTM D638, "Standard Test Method for Tensile Properties of Plastics", a dog–bone shaped specimen is subjected to a constant rate of pull. The "apparent modulus" under this method is the ratio of stress to strain that is achieved at a certain defined strain. This apparent modulus is of limited value for engineering design.

(3) The dynamic modulus is the ratio of stress to strain that occurs under instantaneous rate of increasing stress, such as can occur in a water-hammer reaction in a pipeline. This modulus is used as a parameter for the computing of a localized surge pressure that results from a water hammer event.

B.2.2 – Values for Other Temperatures

The values for other temperatures may be determined by applying a multiplier, as follows, to the base temperature value:

- For Short-Term Apparent Modulus – Apply the multipliers in Table B.1.2
- For Dynamic Apparent Modulus – Apply the multipliers in Table B.2.2

TABLE B.2.2
Dynamic Modulus, Temperature Compensating Multipliers

Temperature , °F (°C)	Multiplier
40 (4)	1.78
50 (10)	1.52
60 (16)	1.28
73.4 (23)	1.00
80 (27)	0.86
90 (32)	0.69
100 (38)	0.53
110 (43)	0.40
120 (49)	0.29

WHERE

P_L = vertical soil pressure due to surcharge pressure, lb/ft^2

p_a = pressure due to sub-area a, lb/ft^2

p_b = pressure due to sub-area b, lb/ft^2

p_c = pressure due to sub-area c, lb/ft^2

p_d = pressure due to sub-area d, lb/ft^2

Pressure due to the surcharge applied to the i-th sub-area equals:

(3-7) $$p_i = I_V \; w_S$$

WHERE

I_V = Influence Value from Table 3-6

w_S = distributed pressure of surcharge load at ground surface, lb/ft^2

If the four sub-areas are equivalent, then Equation 3-7 may be simplified to:

(3-8) $$P_L = 4I_V \; w_S$$

The influence value is dependent upon the dimensions of the rectangular area and upon the depth to the pipe crown, H. Table 3-6 Influence Value terms depicted in Figure 3-6, are defined as:

= depth of cover, ft

= horizontal distance, normal to the pipe centerline, from the center of the load to the load edge, ft

= horizontal distance, parallel to the pipe centerline, from the center of the load to the load edge, ft

Interpolation may be used to find values not given in Table 3-6. The influence value gives the portion (or influence) of the load that reaches a given depth beneath the corner of the loaded area.

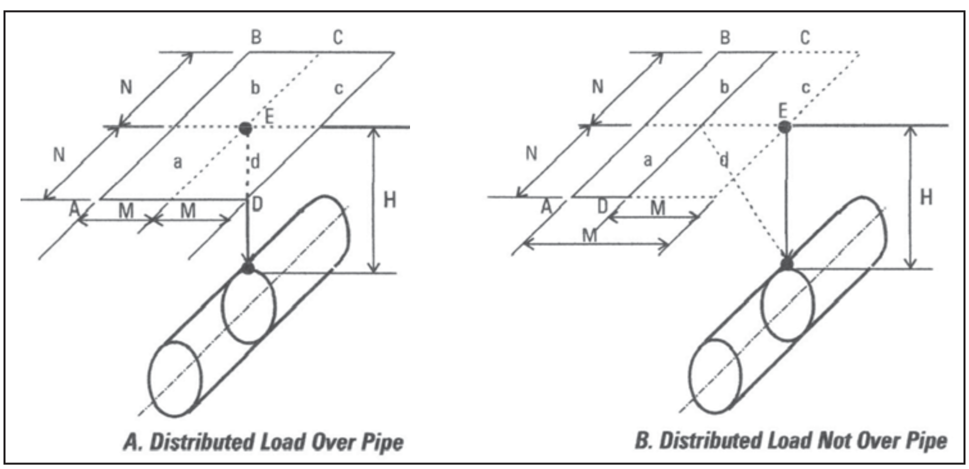


Figure 3-5 Illustration of Distributed Loads

and if half-full, the liquid weight is

(3-36)

$$W_L = \omega_L \frac{\pi d'^2}{8}$$

WHERE

ω_L **= unit weight of the liquid in the pipe, lb/ft3**

d' **= pipe inside diameter, ft**

For liquid levels between empty and half-full (0% to 50%), or between half-full and full (50% to 100%), the following formulas provide an approximate liquid weight with an accuracy of about ±10%. Please refer to Figure 3-8.

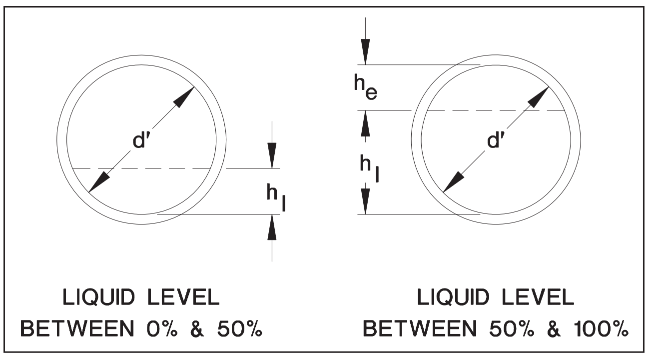


Figure 3-8 Flotation and Internal Liquid Levels

For a liquid level between empty and half-full, the weight of the liquid in the pipe is approximately

(3-37)

$$W_L = \omega_L \frac{4 h_l^{\,3}}{3} \sqrt{\frac{d' - h_l}{h_l} + 0.392}$$

WHERE

hl **= liquid level in pipe, ft**

For a liquid level between half-full and full, the weight of the liquid in the pipe is approximately

(3-38)

$$W_L = \omega_L \left(\frac{\pi d'^2}{4} \quad . \quad 3h \right)$$

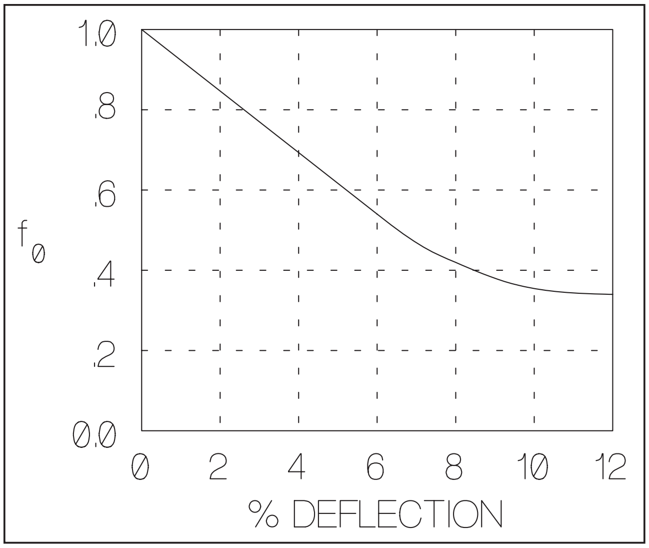


Figure 3-9 Ovality Compensation Factor, $f_{\text{ø}}$

The designer should compare the critical buckling pressure with the actual anticipated pressure, and apply a safety factor commensurate with their assessment of the application. A safety factor of 2.5 is common, but specific circumstances may warrant a higher or lower safety factor. For large-diameter submerged pipe, the anticipated pressure may be conservatively calculated by determining the height of water from the pipe invert rather than from the pipe crown.

Ground Water Flotation Example

Find the allowable flood water level above a 10" DR 26 PE4710 pipe installed with only 2 ft of cover. Assume the pipe has 3 percent ovality due to shipping, handling, and installation loads.

SOLUTION: Use Equation 3-39. The pipe wall buckling pressure depends upon the duration of the water level above the pipe. If the water level is long lasting, then a long-term value of the stress relaxation modulus should be used, but if the water level rises only occasionally, a shorter term elastic modulus may be applied.

Case (a): For the long lasting water above the pipe, the stress relaxation modulus at 50 year, 73°F is approximately 29,000 lb/in² for a typical PE4710 material. Assuming 3% ovality (f_O equals 0.76) and a 2.5 to 1 safety factor, the allowable long-term pressure, P_{WU} is given by:

$$P_{WU} = \frac{(0.76)}{2.5}\frac{2(2\ \ ,000)}{(1-0.45^2)}\left(\frac{1}{26-1}\right)^3 = 1.4\ psi \quad (3.2\ ft\text{-}\ \ d)$$

TABLE 3-8

Values of E' for Pipe Embedment (See Duncan and Hartley[10])

Type of Soil	Depth of Cover, ft	E' for Standard AASHTO Relative Compaction, lb/in^2			
		85%	90%	95%	100%
Fine-grained soils with less than 25% sand content (CL, ML, CL-ML)	0-5	500	700	1000	1500
	5-10	600	1000	1400	2000
	10-15	700	1200	1600	2300
	15-20	800	1300	1800	2600
Coarse-grained soils with fines (SM, SC)	0-5	600	1000	1200	1900
	5-10	900	1400	1800	2700
	10-15	1000	1500	2100	3200
	15-20	1100	1600	2400	3700
Coarse-grained soils with little or no fines (SP, SW, GP, GW)	0-5	700	1000	1600	2500
	5-10	1000	1500	2200	3300
	10-15	1050	1600	2400	3600
	15-20	1100	1700	2500	3800

Soil Support Factor, F_S

Ring deflection and the accompanying horizontal diameter expansion create lateral earth pressure which is transmitted through the embedment soil and into the trench sidewall. This may cause the sidewall soil to compress. If the compression is significant, the embedment can move laterally, resulting in an increase in pipe deflection. Sidewall soil compression is of particular concern when the insitu soil is loose, soft, or highly compressible, such as marsh clay, peat, saturated organic soil, etc. The net effect of sidewall compressibility is a reduction in the soil-pipe system's stiffness. The reverse case may occur as well if the insitu soil is stiffer than the embedment soil; e.g. the insitu soil may enhance the embedment giving it more resistance to deflection. The Soil Support Factor, F_S, is a factor that may be applied to E' to correct for the difference in stiffness between the insitu and embedment soils. Where the insitu soil is less stiff than the embedment, F_S is a reduction factor. Where it is stiffer, F_S is an enhancement factor, i.e. greater than one.

The Soil Support Factor, F_S, may be obtained from Tables 3-9 and 3-10 as follows:

- Determine the ratio B_d/D_O, where B_d equals the trench width at the pipe springline (inches), and D_O equals the pipe outside diameter (inches).
- Based on the native insitu soil properties, find the soil reaction modulus for the insitu soil, E'_N in Table 3-9.
- Determine the ratio E'_N/E'.
- Enter Table 3-10 with the ratios B_d/D_O and E'_N/E' and find F_S.

TABLE 3-9
Values of E'_N, Native Soil Modulus of Soil Reaction, Howard [3]

Native In Situ Soils				
Granular		Cohesive		E'_N (psi)
Std. Pentration ASTM D1586 Blows/ft	Description	Unconfined Compressive Strength (TSF)	Description	
> 0 - 1	very, very loose	> 0 - 0.125	very, very soft	50
1 - 2	very loose	0.125 - 0.25	very soft	200
2 - 4	very loose	0.25 - 0.50	soft	700
4 - 8	loose	0.50 - 1.00	medium	1,500
8 - 15	slightly compact	1.00 - 2.00	stiff	3,000
15 - 30	compact	2.00 - 4.00	very stiff	5,000
30 - 50	dense	4.00 - 6.00	hard	10,000
> 50	very dense	> 6.00	very hard	20,000
Rock	–	–	–	50,000

TABLE 3-10
Soil Support Factor, F_S

E'_N/E'	B_d/D_O 1.5	B_d/D_O 2.0	B_d/D_O 2.5	B_d/D_O 3.0	B_d/D_O 4.0	B_d/D_O 5.0
0.1	0.15	0.30	0.60	0.80	0.90	1.00
0.2	0.30	0.45	0.70	0.85	0.92	1.00
0.4	0.50	0.60	0.80	0.90	0.95	1.00
0.6	0.70	0.80	0.90	0.95	1.00	1.00
0.8	0.85	0.90	0.95	0.98	1.00	1.00
1.0	1.00	1.00	1.00	1.00	1.00	1.00
1.5	1.30	1.15	1.10	1.05	1.00	1.00
2.0	1.50	1.30	1.15	1.10	1.05	1.00
3.0	1.75	1.45	1.30	1.20	1.08	1.00
5.0	2.00	1.60	1.40	1.25	1.10	1.00

Lag Factor and Long-Term Deflection

Spangler observed an increase in ring deflection with time. Settlement of the backfill and consolidation of the embedment under the lateral pressure from the pipe continue to occur after initial installation. To account for this, he recommended applying a lag factor to the Iowa Formula in the range of from 1.25 to 1.5. Lag occurs in installations of both plastic and metal pipes. Howard [3, 11] has shown that the lag factor varies with the type of embedment and the degree of compaction. Many plastic pipe designers use a Lag Factor of 1.0 when using the prism load as it

Appendix C
Allowable Compressive Stress

Table C.1 lists allowable compressive stress values for 73°F (23°C). Values for allowable compressive stress for other temperatures may be determined by application of the same multipliers that are used for pipe pressure rating (See Table A.2).

TABLE C.1
Allowable Compressive Stress for 73°F (23°C)

	Pe Pipe Material Designation Code (1)					
	PE 2406 PE 2708		PE3408 PE 3608 PE 3708 PE 3710 PE 4708		PE 4710	
	psi	MPa	psi	MPa	psi	MPa
Allowable Compressive Stress	800	5.52	1000	6.90	1150	7.93

(1) See Chapter 5 for an explanation of the PE Pipe Material Designation Code.

Appendix D
Poisson's Ratio

Poisson's Ratio for ambient temperature for all PE pipe materials is approximately 0.45.

This 0.45 value applies both to the condition of tension and compression. While this value increases with temperature, and vice versa, the effect is relatively small over the range of typical working temperatures.

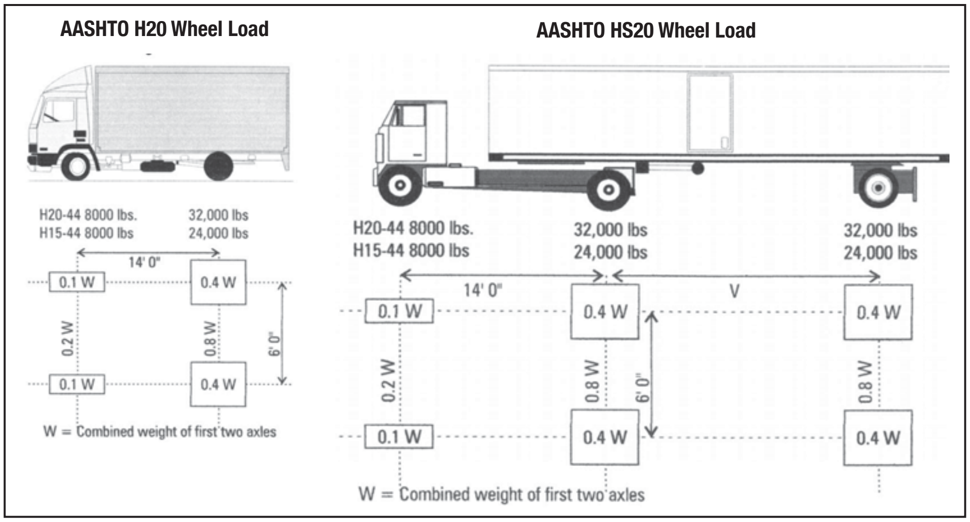


Figure 3-3 AASHTO H20 and HS20 Vehicle Loads

Impact Factor

Road surfaces are rarely smooth or perfectly even. When vehicles strike bumps in the road, the impact causes an instantaneous increase in wheel loading. Impact load may be found by multiplying the static wheel load by an impact factor. The factor varies with depth. Table 3-2 gives impact factors for vehicles on paved roads. For unpaved roads, impact factors of 2.0 or higher may occur, depending on the road surface.

TABLE 3-2
Typical Impact Factors for Paved Roads

Cover Depth, ft	Impact Factor, I_f
1	1.35
2	1.30
3	1.25
4	1.20
6	1.10
8	1.00

Derived from Illinois DOT dynamic load formula (1996).

Vehicle Loading through Highway Pavement (Rigid)

Pavement reduces the live load pressure reaching a pipe. A stiff, rigid pavement spreads load out over a large subgrade area thus significantly reducing the vertical

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Revised 04-07-2009

IPS Size and Dimension Data

PE4710 (PE3408)

DriscoPlex® Municipal & Industrial & Energy Series/IPS Pipe Data

Pressure Ratings are calculated using 0.63 design factor for HDS at 73°F as listed in PPI TR-4 for PE 4710 materials.
Temperature, Chemical, and Environmental use considerations may require use of additional design factors.

Pressure Rating		317 psi DR 7.3			250 psi DR 9.0			200 psi DR 11.0			160 psi DR 13.5			
IPS Pipe Size	Nominal OD (in)	Minimum Wall (in)	Average ID (in)	Weight (lbs/ft)	Minimum Wall (in)	Average ID (in)	Weight (lbs/ft)	Minimum Wall (in)	Average ID (in)	Weight (lbs/ft)	Minimum Wall (in)	Average ID (in)	Weight (lbs/ft)	IPS Pipe Size
1 1/4"	1.660	0.227	1.179	0.45	0.184	1.270	0.37	0.151	1.340	0.31	0.123	1.399	0.26	1 1/4"
1 1/2"	1.900	0.260	1.349	0.59	0.211	1.453	0.49	0.173	1.533	0.41	0.141	1.601	0.34	1 1/2"
2"	2.375	0.325	1.686	0.92	0.264	1.815	0.77	0.216	1.917	0.64	0.176	2.002	0.53	2"
3"	3.500	0.479	2.485	1.99	0.389	2.675	1.66	0.318	2.826	1.39	0.259	2.951	1.16	3"
4"	4.500	0.616	3.194	3.29	0.500	3.440	2.75	0.409	3.633	2.31	0.333	3.794	1.92	4"
6"	6.625	0.908	4.700	7.12	0.736	5.065	5.96	0.602	5.349	5.00	0.491	5.584	4.15	6"
8"	8.625	1.182	6.119	12.07	0.958	6.594	10.11	0.784	6.963	8.47	0.639	7.270	7.04	8"
10"	10.750	1.473	7.627	18.75	1.194	8.219	15.70	0.977	8.679	13.16	0.796	9.062	10.93	10"
12"	12.750	1.747	9.046	26.38	1.417	9.746	22.08	1.159	10.293	18.51	0.944	10.749	15.38	12"
14"	14.000	1.918	9.934	31.81	1.556	10.701	26.63	1.273	11.301	22.32	1.037	11.802	18.54	14"
16"	16.000	2.192	11.353	41.55	1.778	12.231	34.78	1.455	12.915	29.15	1.185	13.488	24.22	16"
18"	18.000	2.466	12.772	52.58	2.000	13.760	44.02	1.636	14.532	36.89	1.333	15.174	30.65	18"
20"	20.000	2.740	14.191	64.91	2.222	15.289	54.34	1.818	16.146	45.54	1.481	16.860	37.84	20"
22"	22.000	3.014	15.610	78.55	2.444	16.819	65.75	2.000	17.760	55.10	1.630	18.544	45.79	22"
24"	24.000	3.288	17.029	93.48	2.667	18.346	78.25	2.182	19.374	65.58	1.778	20.231	54.49	24"
26"	26.000				2.889	19.875	91.84	2.364	20.988	76.96	1.926	21.917	63.95	26"
28"	28.000				3.111	21.405	106.51	2.545	22.605	89.26	2.074	23.603	74.17	28"
30"	30.000				3.333	22.934	122.27	2.727	24.219	102.47	2.222	25.289	85.14	30"
32"	32.000							2.909	25.833	116.58	2.370	26.976	96.87	32"
34"	34.000							3.091	27.447	131.61	2.519	28.660	109.36	34"
36"	36.000							3.273	29.061	147.55	2.667	30.346	122.60	36"
42"	42.000										3.111	35.405	166.88	42"
48"	48.000													48"
54"	54.000													54"

Pipe weights are calculated in accordance with PPI TR-7. Average inside diameter is calculated using nomnal OD and Minimum wall plus 6% for use in estimating fluid flows. Actual ID will vary. When designing components to fit the pipe ID, refer to pipe dimension and tolerances in the applicable pipe manufacturing specification.

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Revised 04-07-2009

IPS Size and Dimension Data PE4710 (PE3408)

DriscoPlex® Municipal & Industrial & Energy Series/IPS Pipe Data

Pressure Ratings are calculated using 0.63 design factor for HDS at 73°F as listed in PPI TR-4 for PE 4710 materials.
Temperature, Chemical, and Environmental use considerations may require use of additional design factors.

Pressure Rating		125 psi DR 17.0			100 psi DR 21.0			80 psi DR 26.0			63 psi DR 32.5			
IPS Pipe Size	Nominal OD (in)	Minimum Wall (in)	Average ID (in)	Weight (lbs/ft)	Minimum Wall (in)	Average ID (in)	Weight (lbs/ft)	Minimum Wall (in)	Average ID (in)	Weight (lbs/ft)	Minimum Wall (in)	Average ID (in)	Weight (lbs/ft)	IPS Pipe Size
1 1/4"	1.660													1 1/4"
1 1/2"	1.900													1 1/2"
2"	2.375	0.140	2.078	0.43										2"
3"	3.500	0.206	3.063	0.94										3"
4"	4.500	0.265	3.938	1.55	0.214	4.046	1.27							4"
6"	6.625	0.390	5.798	3.36	0.315	5.957	2.75	0.255	6.084	2.24	0.204	6.193	1.81	6"
8"	8.625	0.507	7.550	5.69	0.411	7.754	4.66	0.332	7.921	3.80	0.265	8.063	3.07	8"
10"	10.750	0.632	9.410	8.83	0.512	9.665	7.24	0.413	9.874	5.91	0.331	10.048	4.77	10"
12"	12.750	0.750	11.160	12.43	0.607	11.463	10.19	0.490	11.711	8.31	0.392	11.919	6.71	12"
14"	14.000	0.824	12.253	14.98	0.667	12.586	12.28	0.538	12.859	10.02	0.431	13.086	8.09	14"
16"	16.000	0.941	14.005	19.57	0.762	14.385	16.04	0.615	14.696	13.09	0.492	14.957	10.56	16"
18"	18.000	1.059	15.755	24.77	0.857	16.183	20.30	0.692	16.533	16.57	0.554	16.826	13.37	18"
20"	20.000	1.176	17.507	30.58	0.952	17.982	25.07	0.769	18.370	20.45	0.615	18.696	16.50	20"
22"	22.000	1.294	19.257	37.00	1.048	19.778	30.33	0.846	20.206	24.75	0.677	20.565	19.97	22"
24"	24.000	1.412	21.007	44.03	1.143	21.577	36.10	0.923	22.043	29.45	0.738	22.435	23.76	24"
26"	26.000	1.529	22.759	51.67	1.238	23.375	42.36	1.000	23.880	34.57	0.800	24.304	27.89	26"
28"	28.000	1.647	24.508	59.93	1.333	25.174	49.13	1.077	25.717	40.09	0.862	26.173	32.34	28"
30"	30.000	1.765	26.258	68.80	1.429	26.971	56.40	1.154	27.554	46.02	0.923	28.043	37.13	30"
32"	32.000	1.882	28.010	78.28	1.524	28.769	64.17	1.231	29.390	52.36	0.985	29.912	42.24	32"
34"	34.000	2.000	29.760	88.37	1.619	30.568	72.44	1.308	31.227	59.11	1.046	31.782	47.69	34"
36"	36.000	2.118	31.510	99.07	1.714	32.366	81.21	1.385	33.064	66.27	1.108	33.651	53.46	36"
42"	42.000	2.471	36.761	134.84	2.000	37.760	110.54	1.615	38.576	90.20	1.292	39.261	72.77	42"
48"	48.000	2.824	42.013	176.12	2.286	43.154	144.38	1.846	44.086	117.81	1.477	44.869	95.05	48"
54"	54.000				2.571	48.549	182.73	2.077	49.597	149.10	1.662	50.477	120.29	54"

Pipe weights are calculated in accordance with PPI TR-7. Average inside diameter is calculated using nomnal OD and Minimum wall plus 6% for use in estimating fluid flows. Actual ID will vary. When designing components to fit the pipe ID, refer to pipe dimension and tolerances in the applicable pipe manufacturing specification.