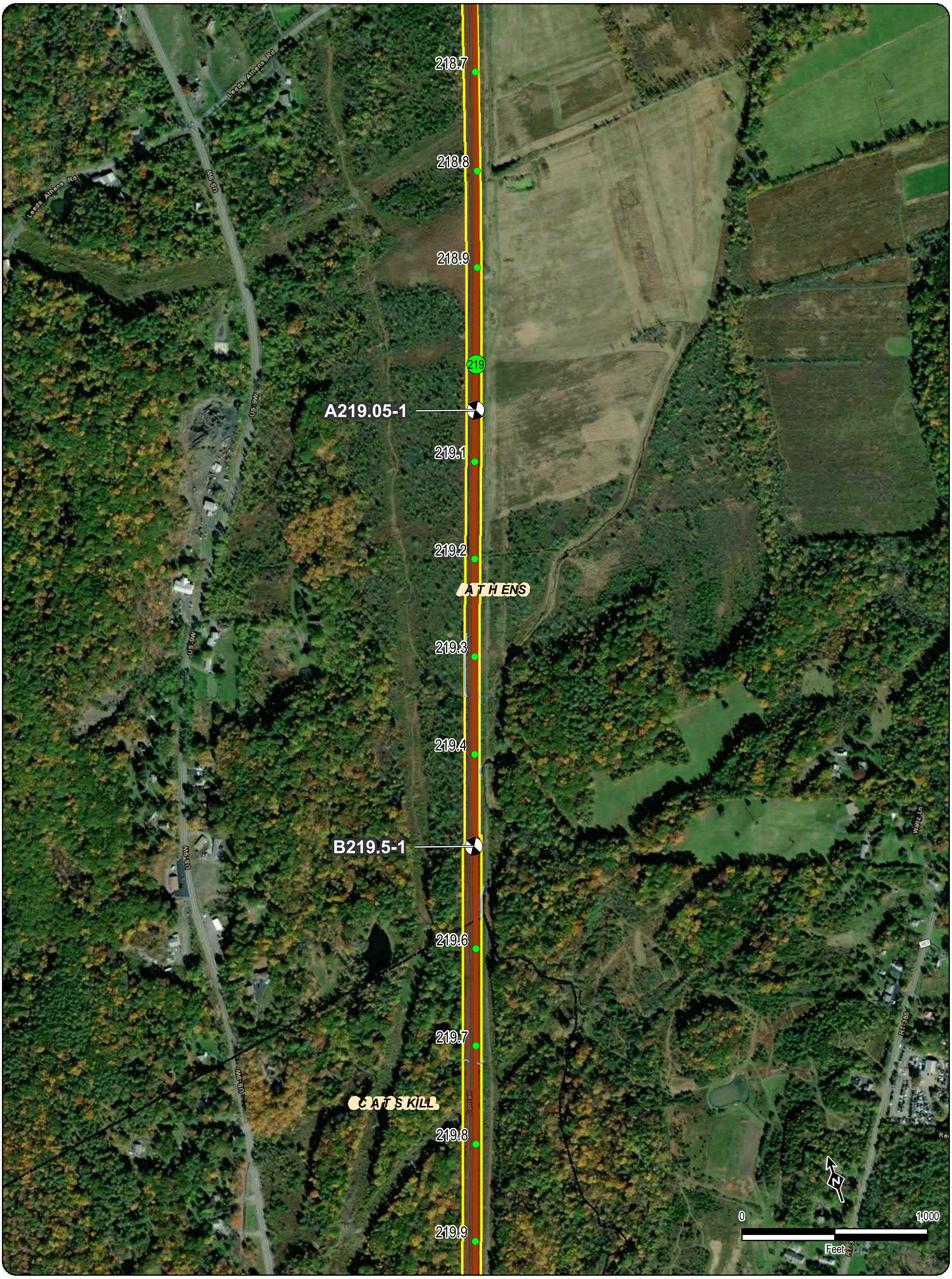
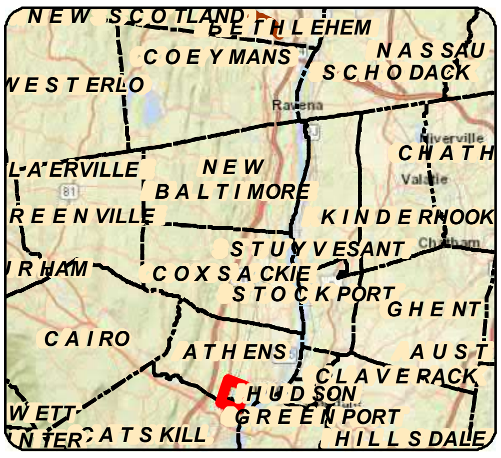




LEGEND

- Certified Milepost - Tenths
- Certified Milepost
- Preferred Alternative Milepost - Tenths
- Preferred Alternative Milepost
- Terrestrial Route HVDC
- Submarine Route HVDC
- Terrestrial Route HVAC
- Preliminary HDD Locations
- Preliminary Pipe Bridge Location
- 2021 Boring Location
- Previous (2013) Boring Location
- Streams/Ditches
- Railroad ROW
- Deviation Zone
- Deviation Zone Outside ROW
- Preferred Alternative Deviation Zone
- Preferred Alternative Deviation Zone Outside ROW
- Town Boundary
- Village Boundary
- State Park (OPRHP)

Parcel Ownership: TOWN NAME

Road Name: Village Name

Transmission Developers Inc.

Champlain Hudson Power Express Project

Champlain Hudson Power Express Inc.

BORING LOCATION PLAN

Selkirk to Catskill

Figure A-10

Sheet 17 of 18

Prepared by: AECOM 5/19/2021

DATA SOURCES: ESRI, NETWORK MAPPING 2010, NYSDOT, OPRHP, TDI, TRC

Y:\Projects\CHPE\Route\Consensus_Alternative_Routes\MXD\Alt_5_Routes_DZ_2019\09Boring_Locations\Maps_for_May_2021_Report\Selkirk_to_Catskill_Boring_Locations_Mapset_May_2021_Report.mxd

TEST BORING LOG

TRC

PROJECT: TDI CHAMPLAIN HUDSON POWER EXPRESS
LOCATION: CSX RAILROAD ROW, NY

BORING	**B219.5-1**
G.S. ELEV.	N/A
FILE	195651
SHEET	1 OF 1

GROUNDWATER DATA

FIRST ENCOUNTERED 13.5 '

DEPTH	HOUR	DATE	ELAPSED TIME

METHOD OF ADVANCING BOREHOLE

a	FROM	0.0 '	TO	10.0 '
d	FROM	10.0 '	TO	25.0 '

DRILLER R. CARUSO
HELPER C. SMART
INSPECTOR C. POPPE
DATE STARTED 12/05/2012
DATE COMPLETED 12/05/2012

DEPTH	A	B	C	DESCRIPTION	Wn	REMARKS
	S-1	8 7 6 8		***BLACK M/C SANDY F/C GRAVEL-SIZED ROCK FRAGMENTS (FILL)*** 2.0		
	S-2	5 17 9 9		***DARK BROWN M/F/C SAND, SM SILT, SM F/ GRAVEL (FILL)*** 4.0	9.1	
5	S-3	9 50/0.4		***BROWN SILT, SM F/M SAND, TR F/ GRAVEL (FILL)*** 6.0	11.8	
	S-4	6 7 9 13		***DARK BROWN TO BLACK SILTY C/F GRAVEL, SM M/F/C SAND (FILL)***		
10	S-5	5 8 6 13		10.0	14.9	
15	S-6	11 17 17			31.2	WATER TABLE DETERMINED FROM WETNESS OF SAMPLE
				LIGHT BROWN TO BROWN CLAY, TR TO SM SILT, TR F/M SAND		
20	S-7	7 7 7		23.5	28.3	
25	S-8	1 2 1		***GRAY SILT (THIXOTROPHIC)*** 25.0		
				END OF BORING AT 25'		
30						
35						

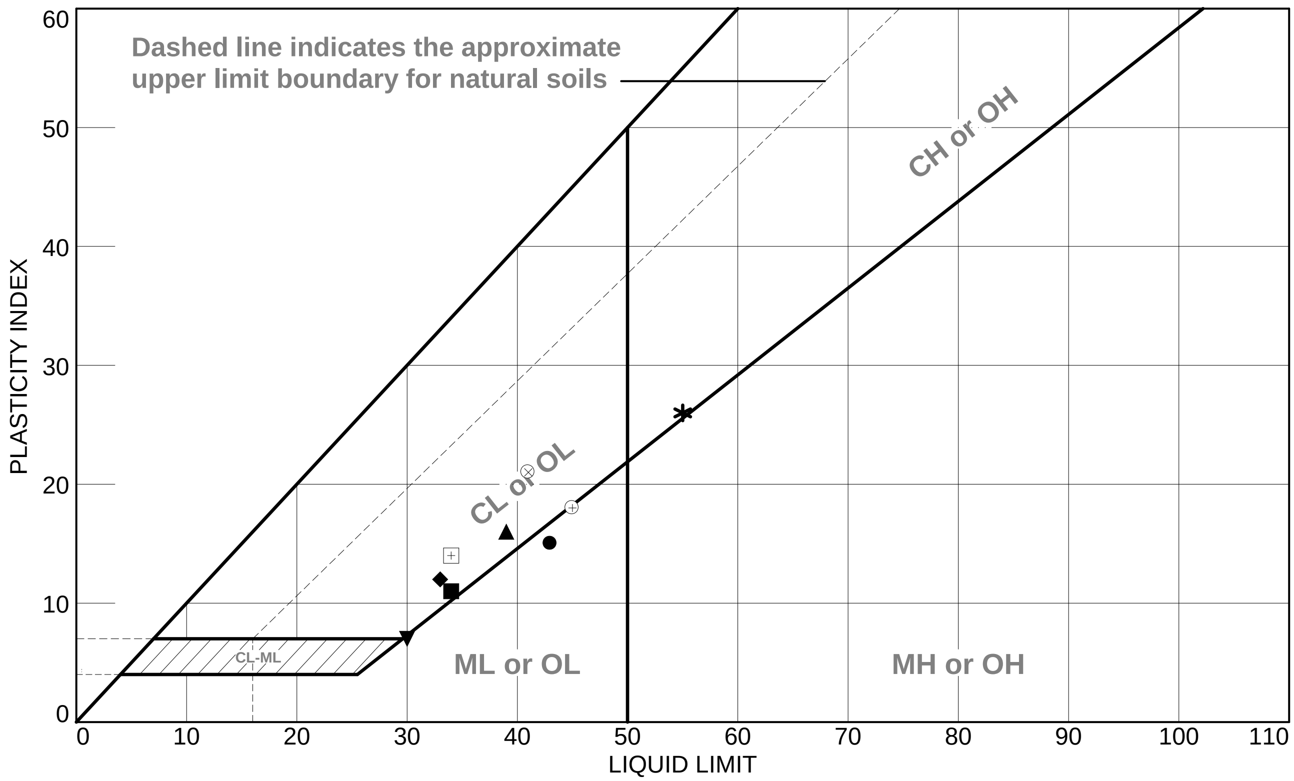
DRN. TBT
CKD. PWK

SUMMARY OF LABORATORY TEST DATA

Project Name: TDI Champlain Hudson Power Express – CSX
Client Name: Transmission Developers, Inc.
TRC Project #: 195651

SAMPLE IDENTIFICATION			Soil Group (USCS System)	GRAIN SIZE DISTRIBUTION				PLASTICITY				Specific Gravity	Moisture Content (%)	Unit Weight (pcf)	Compressive Strength (tsf)	Organic Content (%)
Boring #	Sample #	Depth (ft)		Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquidity Index)					
	S-5	8.0-10.0	CH/MH					56	30	26	0.0	-	30.2	-	-	-
	S-6	13.5-15.0	ML	-	-	-	-	43	28	15	0.5	-	36.0	99.3	-	-
B219.5-1	S-2	2.0-4.0	SM	16.3	62.2	21.5		-	-	-	-	-	9.1	-	-	-
	S-3	4.0-4.9	-	-	-	-	-	-	-	-	-	-	11.8	-	-	-
	S-4	6.0-8.0	GM	35.2	25.6	39.2		-	-	-	-	-	14.9	-	-	-
	S-5	8.0-10.0														
	S-6	13.5-15.0	-	0.0	3.0	14.2	82.8	-	-	-	-	2.83	31.2	99.9	-	-
	S-7	18.5-20.0	CL					34	23	11	0.5	-	28.3	-	-	-
B220.3-1	S-2	2.0-4.0	-	-	-	-	-	-	-	-	-	-	48.8	-	-	10.7
	S-3	4.0-6.0	-	-	-	-	-	-	-	-	-	-	24.0	103.8	-	-
	S-5	8.0-10.0	-	0.0	4.9	23.5	71.5	-	-	-	-	2.80	27.6	-	-	-

LIQUID AND PLASTIC LIMITS TEST REPORT



SOIL DATA

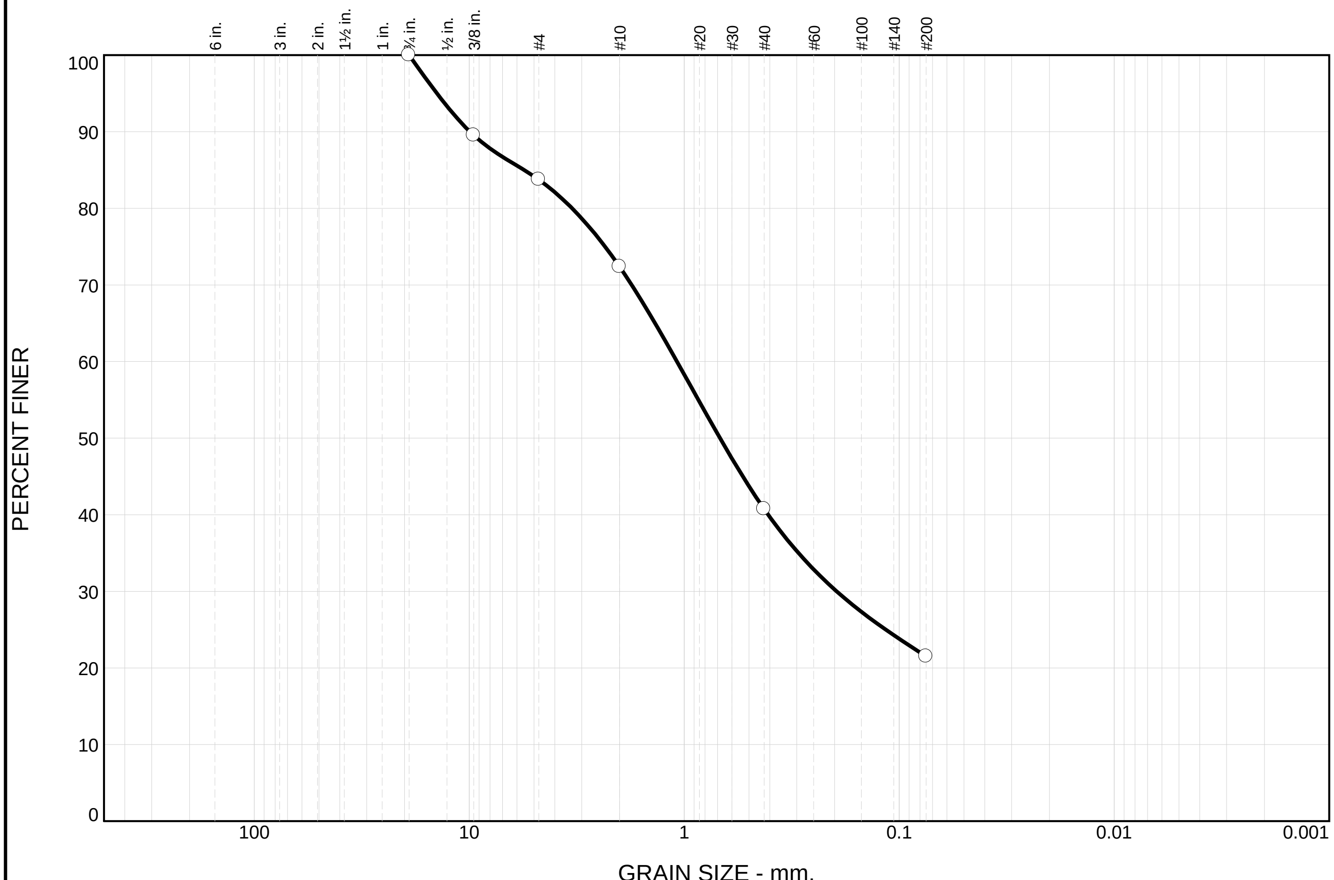
	SOURCE	SAMPLE NO.	DEPTH	NATURAL WATER CONTENT (%)	PLASTIC LIMIT (%)	LIQUID LIMIT (%)	PLASTICITY INDEX (%)	USCS
●	A219.05-1	S-6	13.5-15.0 FT	36.0	28	43	15	ML
■	B219.5-1	S-7	18.5-20.0 FT	28.3	23	34	11	CL
▲	B220.3-1	S-6	13.5-15.0 FT	34.8	23	39	16	CL
◆	B220.3-1	S-7 & S-8	18.5-25.0 FT	26.9	21	33	12	CL
▼	B220.7-1	S-4 & S-5	6.0-10.0 FT	15.4	23	30	7	ML
✱	B221.5-1	S-4 & S-5	6.0-10.0 FT	34.3	29	55	26	CH
⊕	B221.5-1	S-9	28.5-30.0 FT	38.2	27	45	18	CL/ML
⊞	B221.6-1	S-3, S-4, & S-5	4.0-10.0 FT	38.8	20	34	14	CL
⊗	B221.8-1	S-5	8.0-10.0 FT	40.2	20	41	21	CL

TRC
Engineers, Inc.
Mt. Laurel, NJ

Client: TRANSMISSION DEVELOPERS INC.
Project: TDI CHAMPLAIN HUDSON POWER EXPRESS - CSX

Project No.: 195651 **Figure** 8

Particle Size Distribution Report



	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○	0.0	0.0	16.3	11.3	31.7	19.2	21.5	

	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○			5.5542	1.0811	0.6815	0.1955				

	Material Description	USCS	AASHTO
○	DARK BROWN M/F/C SAND, SM SILT, SM F/ GRAVEL	SM	

Project No. 195651 **Client:** TRANSMISSION DEVELOPERS INC.

Project: TDI CHAMPLAIN HUDSON POWER EXPRESS - CSX

○ **Source of Sample:** B219.5-1 **Depth:** 2.0-4.0 FT **Sample Number:** S-2

Remarks:

○SAMPLE DESCRIPTION BASED ON VISUAL IDENTIFICATION AND LABORATORY ANALYSIS

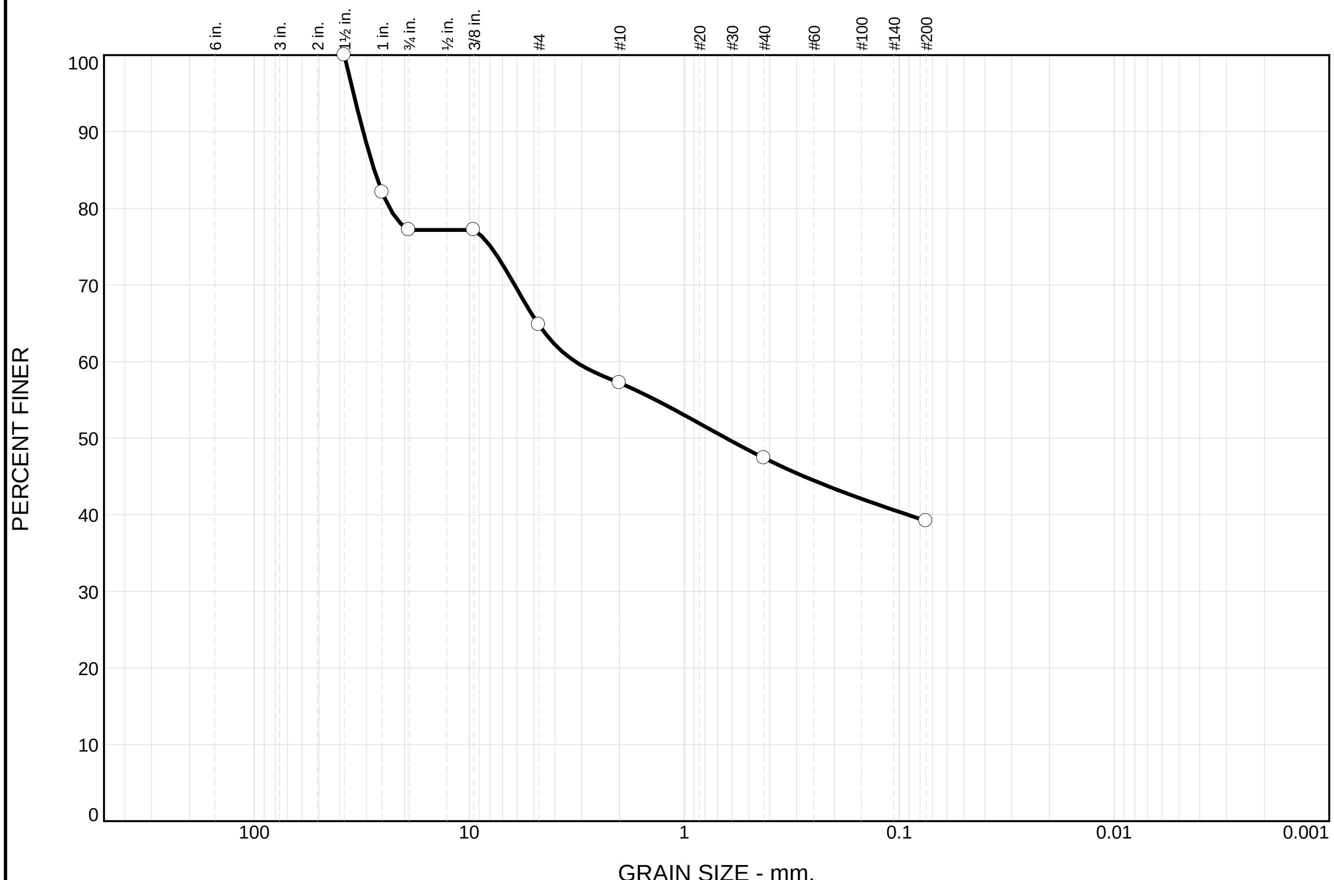
TRC Engineers, Inc.

Mt. Laurel, NJ

Figure 110

Tested By: TBT 01/10/13 **Checked By:** JPB 03/12/13

Particle Size Distribution Report



	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○	0.0	22.8	12.4	7.6	9.8	8.2	39.2	

	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○			27.6551	3.2122	0.6383					

Material Description	USCS	AASHTO
○ DARK BROWN TO BLACK SILTY C/F GRAVEL, SM M/F/C SAND	GM	

Project No. 195651 **Client:** TRANSMISSION DEVELOPERS INC.

Project: TDI CHAMPLAIN HUDSON POWER EXPRESS - CSX

○ **Sample Source:** B219.5-1 **Depth:** 6.0-10.0 FT **Sample No.:** S-4 & S-5

Remarks:
○SAMPLE DESCRIPTION BASED ON VISUAL IDENTIFICAITON AND LABORATORY ANALYSIS

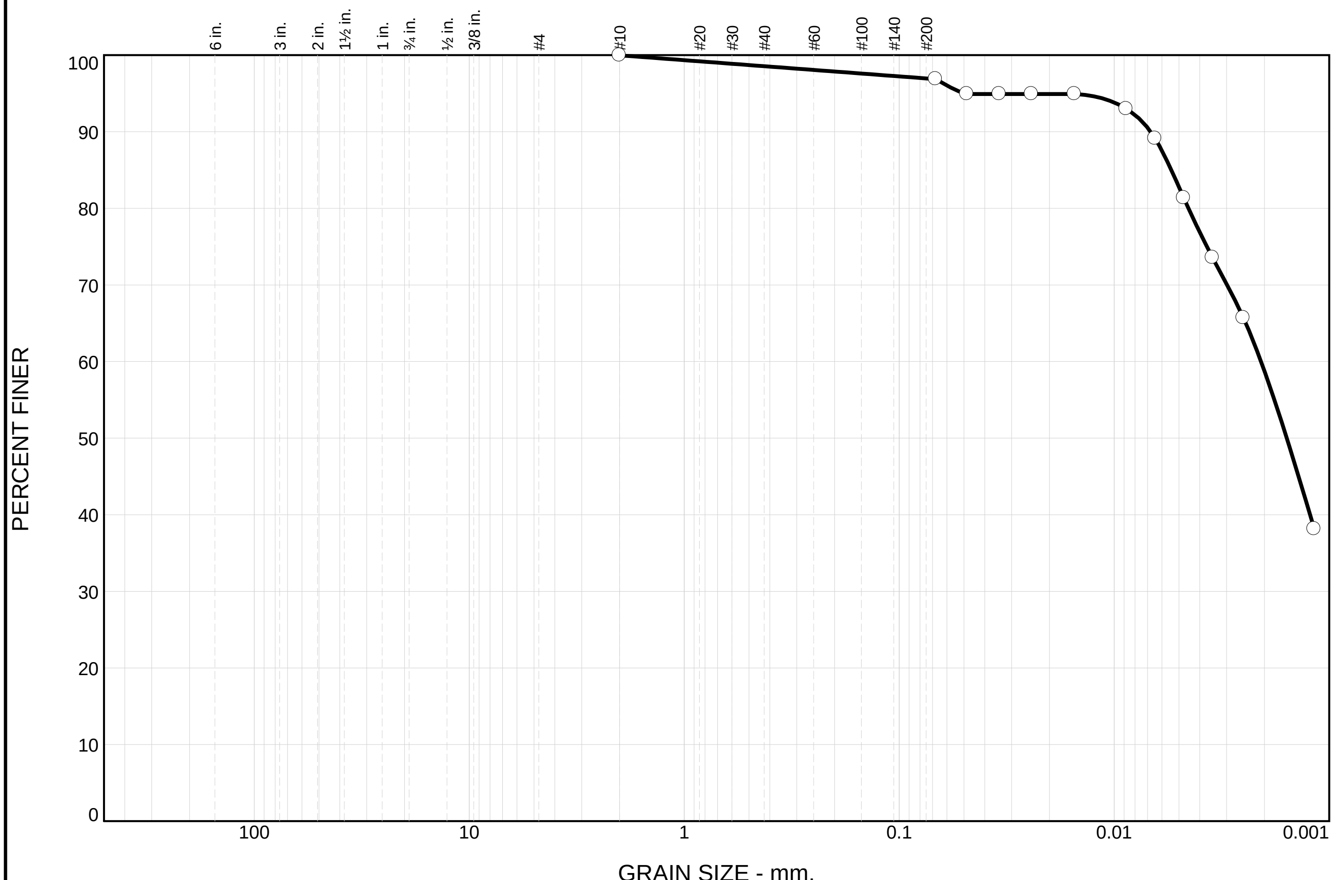
TRC Engineers, Inc.

Mt. Laurel, NJ

Figure 111

Tested By: TBT 01/10/13 **Checked By:** JPB 03/12/13

Particle Size Distribution Report



	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○					1.4	1.6	14.2	82.8

	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○			0.0054	0.0021	0.0016					

Material Description	USCS	AASHTO
○ LIGHT BROWN TO BROWN CLAY, TR TO SM SILT, TR F/M SAND		

Project No. 195651 **Client:** TRANSMISSION DEVELOPERS INC.

Project: TDI CHAMPLAIN HUDSON POWER EXPRESS - CSX

○ **Source of Sample:** B219.5-1 **Depth:** 13.5-15.0 FT **Sample Number:** S-6

Remarks:
○SAMPLE DESCRIPTION BASED ON VISUAL IDENTIFICATION AND LABORATORY ANALYSIS

TRC Engineers, Inc.

Mt. Laurel, NJ

Figure 112

Tested By: TBT 01/08/13 **Checked By:** JPB 03/12/13

EXPLORATION PLAN

Champlain-Hudson Power Express- Phase 4 HDD Borings – Package 6 and 7
Schenectady through Selkirk, NY
April 25, 2023 ■ Terracon Project No. JB215256J

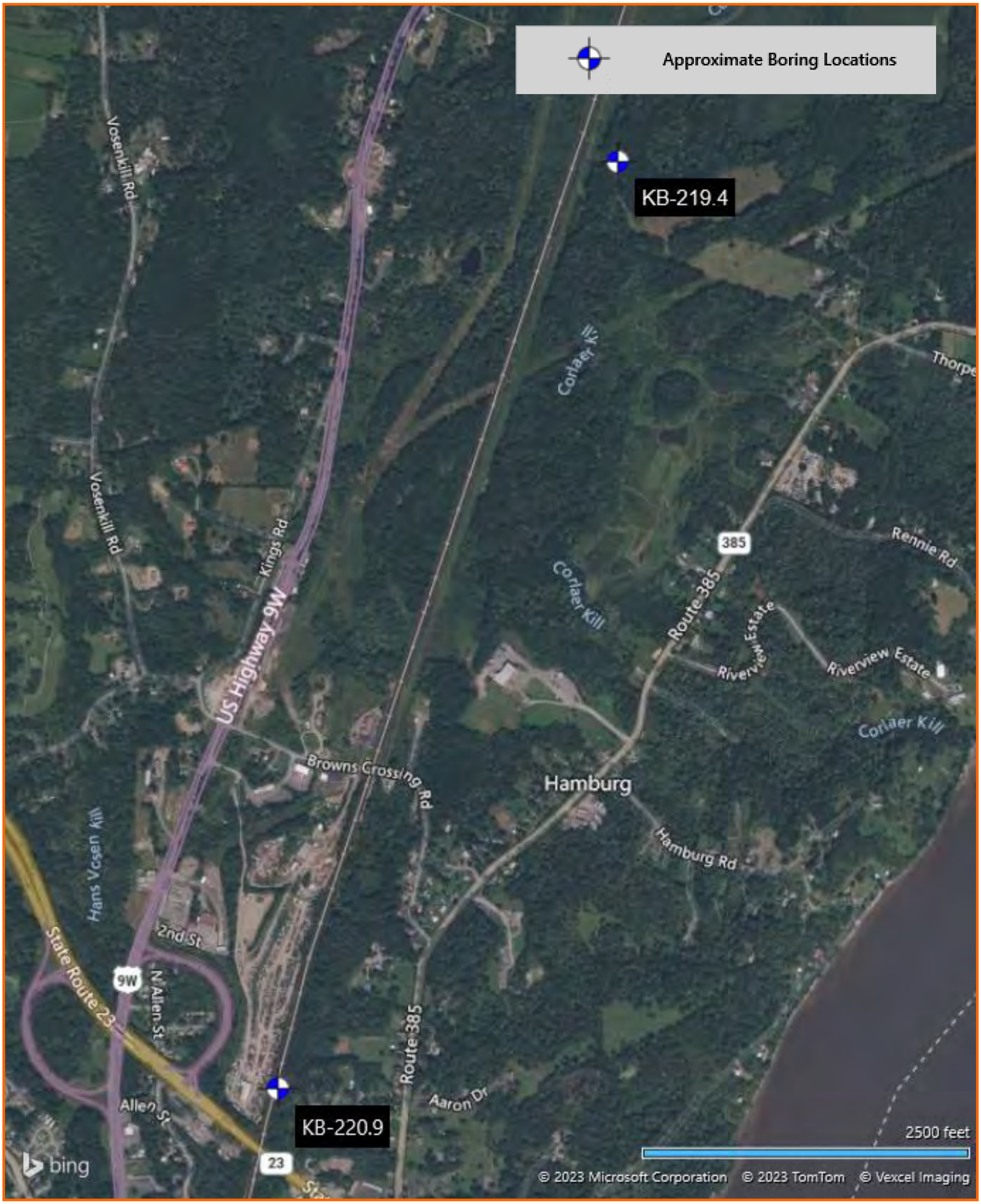


DIAGRAM IS FOR GENERAL LOCATION ONLY, AND IS NOT INTENDED FOR CONSTRUCTION PURPOSES

AERIAL PHOTOGRAPHY PROVIDED BY MICROSOFT BING MAPS

Rock Core – Boring KB-207.1 Run 13 through Run 15

Rock Core – Boring KB-219.4 Run 1 through Run 4

Rock Core – Boring KB-219.4 Run 5 through Run 8

Rock Core – Boring KB-219.4 Run 9 through Run 12

BORING LOG NO. KB-219.4

PROJECT: Phase 4 Borings

CLIENT: Kiewit Engineering (NY) Corp
Lone Tree, CO

SITE: Champlain to Hudson HDD Crossings

LOCATION See Exploration Plan

Latitude: 42.2497° Longitude: -73.8558°

Surface Elev.: 120.73 (Ft.)

DEPTH	Material Description	ELEVATION (Ft.)	DEPTH (Ft.)	WATER LEVEL OBSERVATIONS	SAMPLE TYPE	RECOVERY (In.)	FIELD TEST RESULTS	WATER CONTENT (%)	ATTERBERG LIMITS LL-PL-PI	PERCENT FINES
0.3	**TOPSOIL**	120.4								
	FILL - SANDY SILT, orange and brown				SPT	10	1-2-3-3 N=5			
					SPT	20	5-6-8-8 N=14			
4.0		116.7								
	SILTY GRAVEL WITH SAND (GM), occasional cobbles and boulders, brown, medium dense to dense, (GLACIAL TILL)		5		SPT	20	6-5-8-8 N=13			
					SPT	22	10-10-14-38 N=24	11.8		32
					SPT	12	25-17-20-15 N=37			
			10		SPT	12	18-16-8-7 N=24			
15.0		105.7	15							
	WEATHERED ROCK, gray, very dense						50/0"			
20.0		100.7	20							
	SHALE, occasional calcite veins, unweathered, close to wide fractured with near vertical fractures, good RQD, gray				Core		REC=100% RQD=85%			
25.0		95.7	25							

Stratification lines are approximate. In-situ, the transition may be gradual.

Hammer Type: Automatic

Advancement Method:
0-15' 4" Casing
15-20' Mud Rotary
20' -75' NQ Core Barrel

Abandonment Method:
Boring backfilled with bentonite grout upon completion

See Exploration and Testing Procedures for a description of field and laboratory procedures used and additional data (If any).

See Supporting Information for explanation of symbols and abbreviations.

Elevations were provided by others.

Notes:

Hammer Efficiency Summary:
Energy Transfer Ratio: 89.1% +/-4.4%
Hammer Efficiency Correction (CE): 1.49
Logged by JCH/DO

WATER LEVEL OBSERVATIONS

No free water encountered

Terracon
30 Corporate Cir Ste 201
Albany, NY

Boring Started: 02-15-2023	Boring Completed: 02-16-2023
Drill Rig: Mobil B-57	Driller: J. Swope
Project No.: JB215256J	

BORING LOG NO. KB-219.4

PROJECT: Phase 4 Borings

SITE: Champlain to Hudson HDD Crossings

**CLIENT: Kiewit Engineering (NY) Corp
Lone Tree, CO**

LOCATION See Exploration Plan

Latitude: 42.2497° Longitude: -73.8558°

Surface Elev.: 120.73 (Ft.)

GRAPHIC LOG	DEPTH / DESCRIPTION	ELEVATION (Ft.)	DEPTH (Ft.)	WATER LEVEL OBSERVATIONS	SAMPLE TYPE	RECOVERY (In.)	FIELD TEST RESULTS	WATER CONTENT (%)	ATTERBERG LIMITS LL-PL-PI	PERCENT FINES
	SHALE, occasional calcite veins, inter bedded with greywacke, unweathered, very close to wide fractured, good RQD, gray						REC=95% RQD=78%			
	30.0	90.7	30							
	SHALE, occasional calcite veins, unweathered, close to wide fractured, excellent RQD, gray						REC=100% RQD=90%			
	35.0	85.7	35							
	GREYWACKE, occasional calcite veins, inter bedded with shale, unweathered, very close to wide fractured with occasional high angled fractures, excellent RQD, gray						REC=100% RQD=96%			
	40.0	80.7	40							
	SHALE, occasional calcite veins, inter bedded with greywacke, unweathered, close to moderate fractured, good RQD, gray						REC=100% RQD=80%			
	45.0	75.7	45							
	SHALE, occasional calcite veins, inter bedded with greywacke, unweathered, close to moderate fractured, fair RQD, gray						REC=100% RQD=53%			
	50.0	70.7	50							

Stratification lines are approximate. In-situ, the transition may be gradual.

Hammer Type: Automatic

Advancement Method:
0-15' 4" Casing
15-20' Mud Rotary
20' -75' NQ Core Barrel

Abandonment Method:
Boring backfilled with bentonite grout upon completion

See Exploration and Testing Procedures for a description of field and laboratory procedures used and additional data (If any).

See Supporting Information for explanation of symbols and abbreviations.

Elevations were provided by others.

Notes:

Hammer Efficiency Summary:
Energy Transfer Ratio: 89.1% +/-4.4%
Hammer Efficiency Correction (CE): 1.49
Logged by JCH/DO

WATER LEVEL OBSERVATIONS

No free water encountered

Terracon
30 Corporate Cir Ste 201
Albany, NY

Boring Started: 02-15-2023	Boring Completed: 02-16-2023
Drill Rig: Mobil B-57	Driller: J. Swope
Project No.: JB215256J	

BORING LOG NO. KB-219.4

PROJECT: Phase 4 Borings

CLIENT: Kiewit Engineering (NY) Corp, Lone Tree, CO

SITE: Champlain to Hudson HDD Crossings

LOCATION See Exploration Plan

Latitude: 42.2497° Longitude: -73.8558°

Surface Elev.: 120.73 (Ft.)

DEPTH	Description	ELEVATION (Ft.)	DEPTH (Ft.)	WATER LEVEL OBSERVATIONS	SAMPLE TYPE	RECOVERY (In.)	FIELD TEST RESULTS	WATER CONTENT (%)	ATTERBERG LIMITS LL-PL-PI	PERCENT FINES
	GREYWACKE, occasional calcite veins, inter bedded with shale, unweathered, very close to close fractured with occasional high angled fractures, good RQD, gray						REC=100% RQD=78%			
55.0		65.7	55							
	SHALE, occasional calcite veins, inter bedded with greywacke, unweathered, close to moderate fractured with occasional high angled fractures, excellent RQD, gray						REC=100% RQD=95%			
60.0		60.7	60							
	GREYWACKE, occasional calcite veins, inter bedded with shale, unweathered, wide fractured with occasional high angled fractures, excellent RQD, gray						REC=100% RQD=100%			
65.0		55.7	65							
	GREYWACKE, occasional calcite veins, unweathered, extremely close to wide fractured with occasional high angled fractures, good RQD, gray						REC=96% RQD=78%			
70.0		50.7	70							
	SHALE, occasional calcite veins, unweathered, extremely close to moderate fractured with occasional high angled fractures, good RQD, gray						REC=100% RQD=70%			
75.0		45.7	75							

Stratification lines are approximate. In-situ, the transition may be gradual.

Hammer Type: Automatic

Advancement Method:
- 00-15' 4" Casing
- 15-20' Mud Rotary
- 20' -75' NQ Core Barrel

Abandonment Method:
Boring backfilled with bentonite grout upon completion

See Exploration and Testing Procedures for a description of field and laboratory procedures used and additional data (If any).

See Supporting Information for explanation of symbols and abbreviations.

Elevations were provided by others.

Notes:

Hammer Efficiency Summary:
Energy Transfer Ratio: 89.1% +/-4.4%
Hammer Efficiency Correction (CE): 1.49
Logged by JCH/DO

WATER LEVEL OBSERVATIONS

No free water encountered

Terracon
30 Corporate Cir Ste 201
Albany, NY

Boring Started: 02-15-2023	Boring Completed: 02-16-2023
Drill Rig: Mobil B-57	Driller: J. Swope
Project No.: JB215256J	

BORING LOG NO. KB-219.4

PROJECT: Phase 4 Borings

CLIENT: Kiewit Engineering (NY) Corp
Lone Tree, CO

SITE: Champlain to Hudson HDD Crossings

GRAPHIC LOG	LOCATION See Exploration Plan Latitude: 42.2497° Longitude: -73.8558° Surface Elev.: 120.73 (Ft.) DEPTH / ELEVATION (Ft.)	DEPTH (Ft.)	WATER LEVEL OBSERVATIONS	SAMPLE TYPE	RECOVERY (In.)	FIELD TEST RESULTS	WATER CONTENT (%)	ATTERBERG LIMITS LL-PL-PI	PERCENT FINES
	SHALE, occasional calcite veins, inter bedded with greywacke, unweathered, very close to close fractured with occasional high angled fractures, fair RQD, gray					REC=100% RQD=60%			
	80.0 / 40.7	80							
	Boring Terminated at 80 Feet								

Stratification lines are approximate. In-situ, the transition may be gradual.

Hammer Type: Automatic

Advancement Method:
00-15' 4" Casing
15-20' Mud Rotary
20' -75' NQ Core Barrel

Abandonment Method:
Boring backfilled with bentonite grout upon completion

See Exploration and Testing Procedures for a description of field and laboratory procedures used and additional data (If any).

See Supporting Information for explanation of symbols and abbreviations.

Elevations were provided by others.

Notes:

Hammer Efficiency Summary:
Energy Transfer Ratio: 89.1% +/-4.4%
Hammer Efficiency Correction (CE): 1.49
Logged by JCH/DO

WATER LEVEL OBSERVATIONS

No free water encountered

Terracon
30 Corporate Cir Ste 201
Albany, NY

Boring Started: 02-15-2023	Boring Completed: 02-16-2023
Drill Rig: Mobil B-57	Driller: J. Swope
Project No.: JB215256J	

Summary of Laboratory Results

BORING ID	Depth (Ft.)	Water Content (%)	Liquid Limit	Plastic Limit	Plasticity Index	Organic Content (%)
KB-206.8	4-6	29.4	50	26	24	
KB-206.8	15-17	32.9	40	23	17	
KB-206.8	35-37	11.0	17	13	4	
KB-207.0	4-6	23.7	42	30	12	
KB-207.1	4-6	15.1				
KB-209.7	4-6	30.3	64	32	32	2.8
KB-209.7	15-17	38.8	64	32	32	
KB-209.7	25-27	38.8	54	25	29	
KB-209.7	40-42	38.8	45	25	20	
KB-211.4B	4-6	32.8	58	32	26	
KB-211.4B	15-17	48.0	55	31	24	
KB-211.4B	40-42	36.7	63	32	31	
KB-214.4	4-6	33.7	65	33	32	
KB-214.4	15-17	37.6	57	29	28	
KB-214.4	30-32	49.7	45	30	15	
KB-219.4	6-8	11.8				
KB-220.9	4-6	31.0	50	27	23	
KB-220.9	20-22	39.6	47	26	21	
KB-220.9	45-47	33.6	42	27	15	

PROJECT: Phase 4 Borings

SITE: Champlain to Hudson HDD Crossings

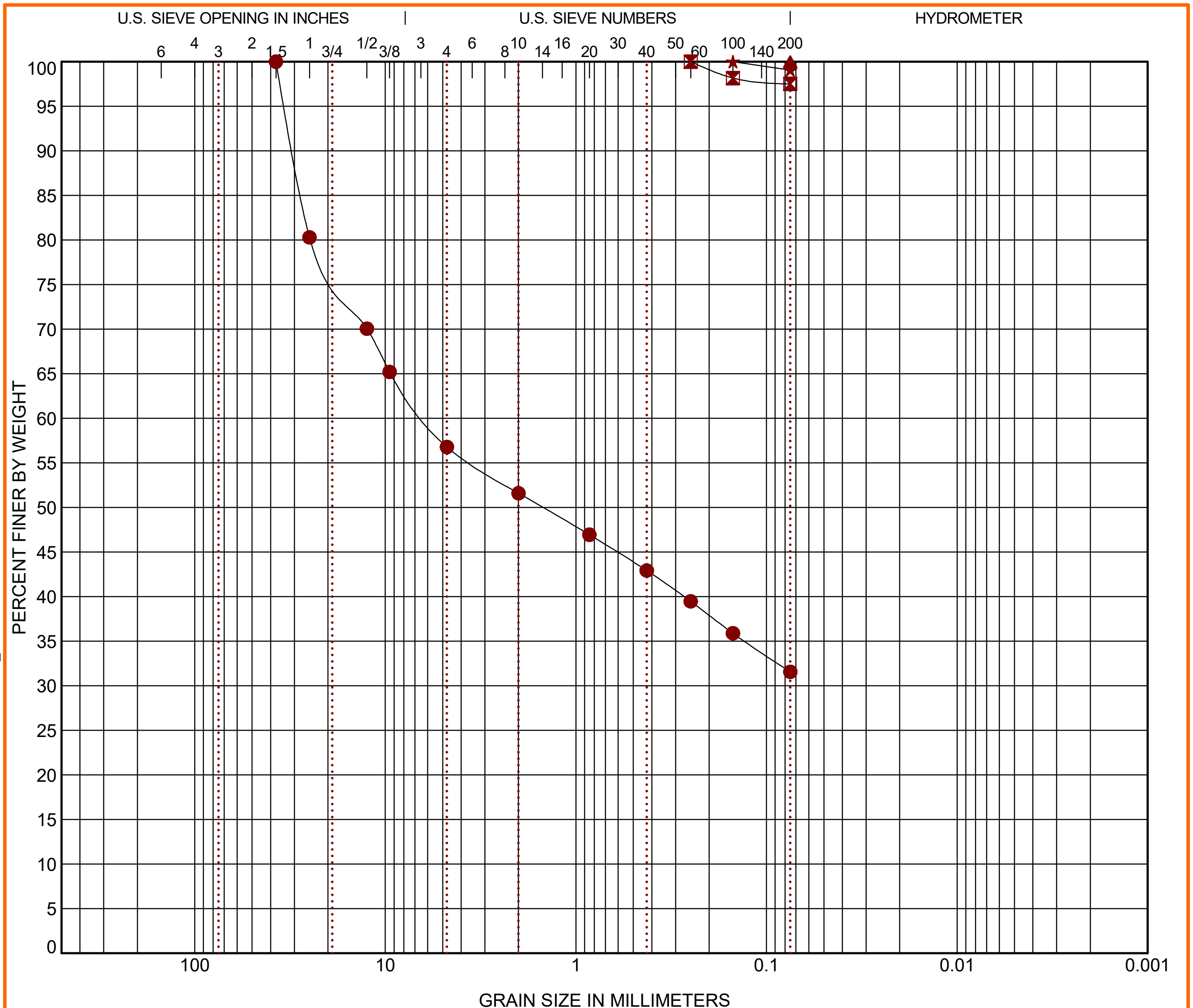
Terracon
30 Corporate Cir Ste 201
Albany, NY

PROJECT NUMBER: JB215256J

CLIENT: Kiewit Engineering (NY) Corp
Lone Tree, CO

GRAIN SIZE DISTRIBUTION

ASTM D422 / ASTM C136



COBBLES	GRAVEL		SAND			SILT OR CLAY
	coarse	fine	coarse	medium	fine	

	Boring ID	Depth (Ft)	USCS Classification	WC (%)	LL	PL	PI	Cc	Cu
●	KB-219.4	6 - 8	SILTY GRAVEL with SAND (GM)	11.8					
⊠	KB-220.9	4 - 6	FAT CLAY (CH)	31.0	50	27	23		
▲	KB-220.9	20 - 22	LEAN CLAY (CL)	39.6	47	26	21		
★	KB-220.9	45 - 47	SILT (ML)	33.6	42	27	15		

	Boring ID	Depth (Ft)	D_{100}	D_{60}	D_{30}	D_{10}	%Cobbles	%Gravel	%Sand	%Silt	%Fines	%Clay
●	KB-219.4	6 - 8	37.5	6.191			0.0	43.2	25.2		31.6	
⊠	KB-220.9	4 - 6	0.25				0.0	0.0	2.5		97.5	
▲	KB-220.9	20 - 22	0.075				0.0	0.0	0.0		100.0	
★	KB-220.9	45 - 47	0.15				0.0	0.0	0.9		99.1	

PROJECT: Phase 4 Borings

PROJECT NUMBER: JB215256J

SITE: Champlain to Hudson HDD Crossings

Terracon
30 Corporate Cir Ste 201
Albany, NY

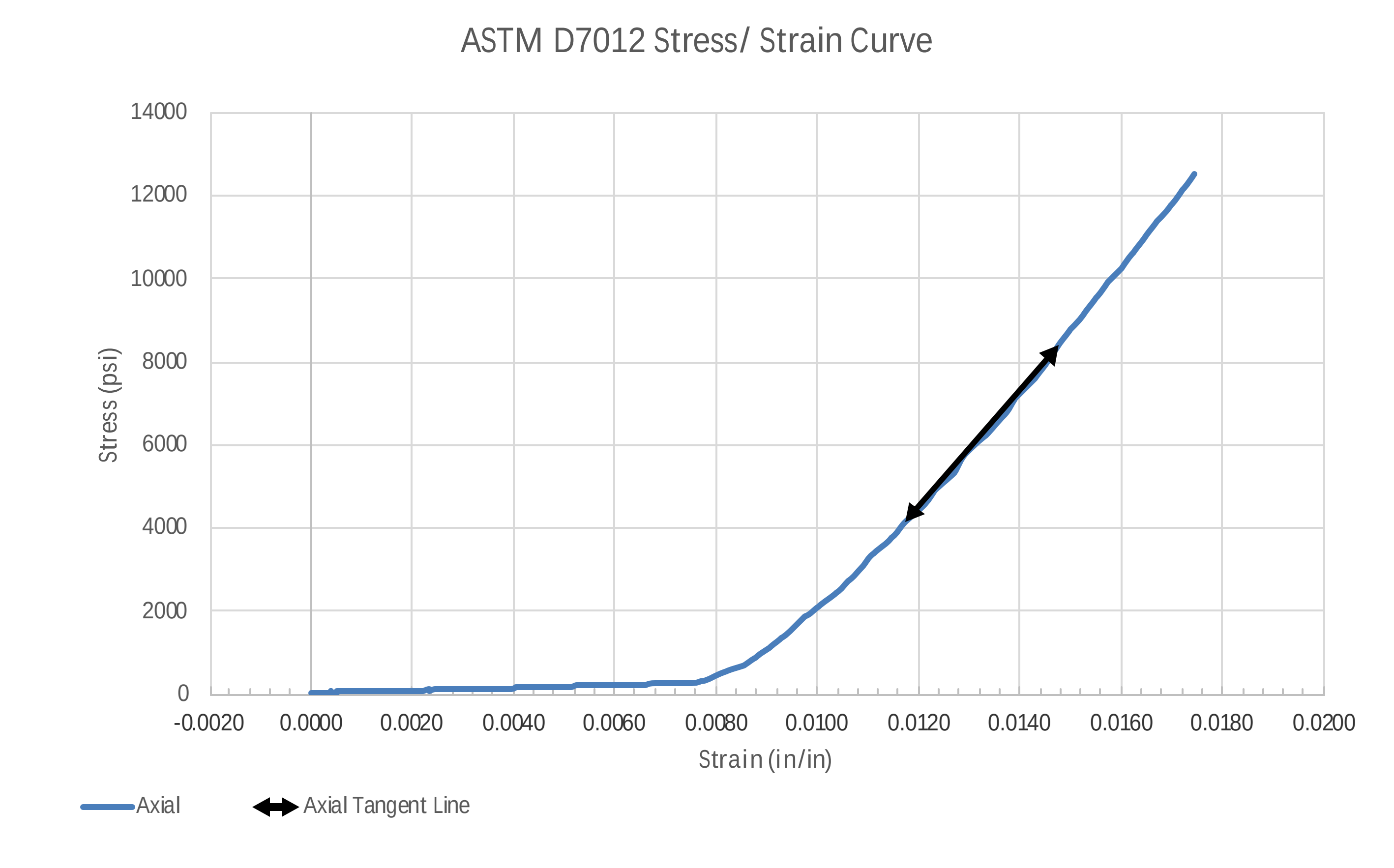
CLIENT: Kiewit Engineering (NY) Corp
Lone Tree, CO

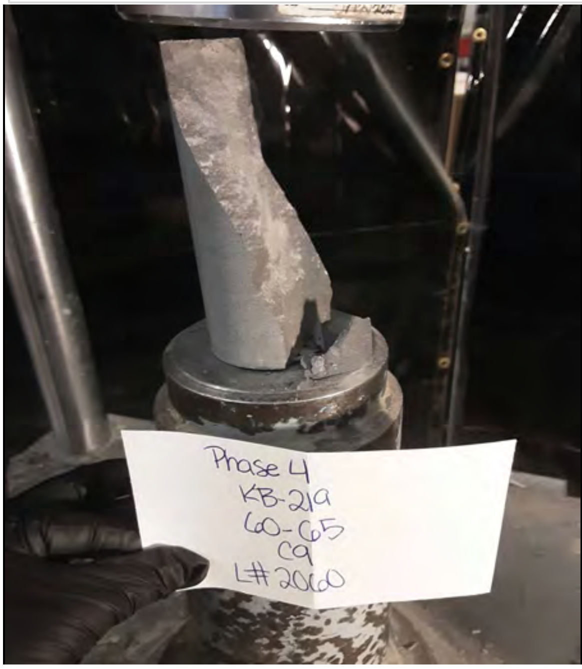
Rock Core D7012 Method C

Client
Kiewit Engineering

Project
Phase 4 Borings

Project No. JB215256J





SAMPLE LOCATION			
Site:	Phase 4 Borings		
Description:	Greywacke		
Boring:	KB-219.4	Depth (feet):	60.0-65.0

SPECIMEN INFORMATION			
Sample No.:	C-9	Mass (g):	564.96
Length (in.):	4.12	Diameter (in.):	1.98
L/D Ratio:	2.08	Density (pcf):	169.66

TEST RESULTS	
Failure Load (lbs):	38578
Failure Strain (in/in):	0.020
Unconfined Compressive Strength (psi):	12,529
Elastic Modulus, E, (ksi):	1403
Time of Failure (min):	03:20
Rate of Loading (in/sec):	0.04
Moisture Content Post-break:	0.40%

Rock Core D7012 Method C

Client	Project
Kiewit Engineering	Phase 4 Borings
	Project No. JB215256J

Equipment:

	TICCS ID:
Calipers	W-44049
Scale	B-71466
Dial Indicator	C-70608
Compression (spherically seated)	C-48999

Samples were prepared and tested in accordance with ASTM D4543 and D7012. Deviations, if any, are noted below:

Notes:

Per ASTM D4543, this specimen has not met the requirements for flatness, by exceeding 0.001 inches.
Per ASTM D4543, this specimen has not met the requirements for parallelism, by exceeding 0.25º.
Per ASTM D4543, this specimen has not met the requirements for flatness, by exceeding 0.001 inches.
Per ASTM D4543 and ASTM D7012, the desired specimen length to diameter are between 2.0:1 and 2.5:1.
According to ASTM D7012 Section 8.2.1, this specimen, although not meeting all requirements of ASTM D4543 is acceptable for testing. However, the results reported may differ from results obtained from a test specimen that meets the requirements of D4543.

Client
Kiewit Engineering

Project
Phase 4 Borings

Project No. JB215256J

Splitting Tensile Strength of Intact Rock Core Specimens, ASTM D3967

Boring	KB-219.4	**Material Description**	Greywacke
Sample No	C-9	**Equipment Used**	Tinius Olsen (120,000lbs)
Depth (ft)	60.0-65.0	**TICCS ID/Serial No.**	C-48999, 118285
Lab No	2060	**Calibration Date**	11/2/2022

	TENSILE STRENGTH				
Lab No.	1	2	3	4	5
Diameter (in)	1.98	1.98	1.98	1.98	--
Length (in)	0.64	0.68	0.68	0.70	--
Length Diameter Ratio	0.32	0.34	0.34	0.35	--
Rate of Loading	0.0064	0.0068	0.0068	0.0070	--
Moisture Condition	0.43%	0.43%	0.43%	0.43%	--
Maximum Applied Load (lbf)	4851	6229	4557	4142	--
Splitting Tensile Strength (psi)	2438.3	2946.8	2155.8	1903.5	--

	TENSILE STRENGTH				
Lab No.	6	7	8	9	10
Diameter (in)	--	--	--	--	--
Length (in)	--	--	--	--	--
Length Diameter Ratio	--	--	--	--	--
Rate of Loading	--	--	--	--	--
Moisture Condition	--	--	--	--	--
Maximum Applied Load (lbf)	--	--	--	--	--
Splitting Tensile Strength (psi)	--	--	--	--	--

GeoTesting EXPRESS

Client:	Terracon Consultants, Inc.		
Project:	Champlain-Hudson Power Express		
Location:	---	Project No:	GTX-316884
Boring ID: KB-219.4	Sample Type: cylinder	Tested By:	tlm
Sample ID: ---	Test Date: 03/09/23	Checked By:	smd
Depth : 60'-65'	Test Id: 707603		
Test Comment:	---		
Visual Description:	---		
Sample Comment:	---		

Abrasiveness of Rock Using the Cerchar Method by ASTM D7625

Boring ID	Sample ID	Depth	Stylus No	Reading 1	Reading 2	Average	Comments
KB-219.4	---	60-65 ft	1	0.2	0.2	0.20	
			2	0.3	0.4	0.35	
			3	0.3	0.4	0.35	
			4	0.2	0.2	0.20	
			5	0.3	0.4	0.35	
			Average CAIs			0.29	
			Average CAI *			0.77	
CERCHAR Abrasiveness Index Classification						**Low abrasiveness**	

Notes

Test Surface: Saw Cut
Moisture Condition: As Received
Apparatus Type: Original CERCHAR
Stylus Hardness: Rockwell Hardess 40/42 HRC
Stylus Displacement Relative to Rock Fabric:
Styli 1-3: Normal; Styli 4-5: Parallel
* CAI = (0.99 * CAIs) + 0.48
CAIs = CERCHAR index for smooth (saw cut) surface
CAI = CERCHAR index for natural surface
Comments:

EXPLORATION PLAN
Champlain-Hudson Power Express- Phase 4 HDD Borings – Package 6 and 7
Schenectady through Selkirk, NY
May 31, 2023 ■ Terracon Project No. JB215256J

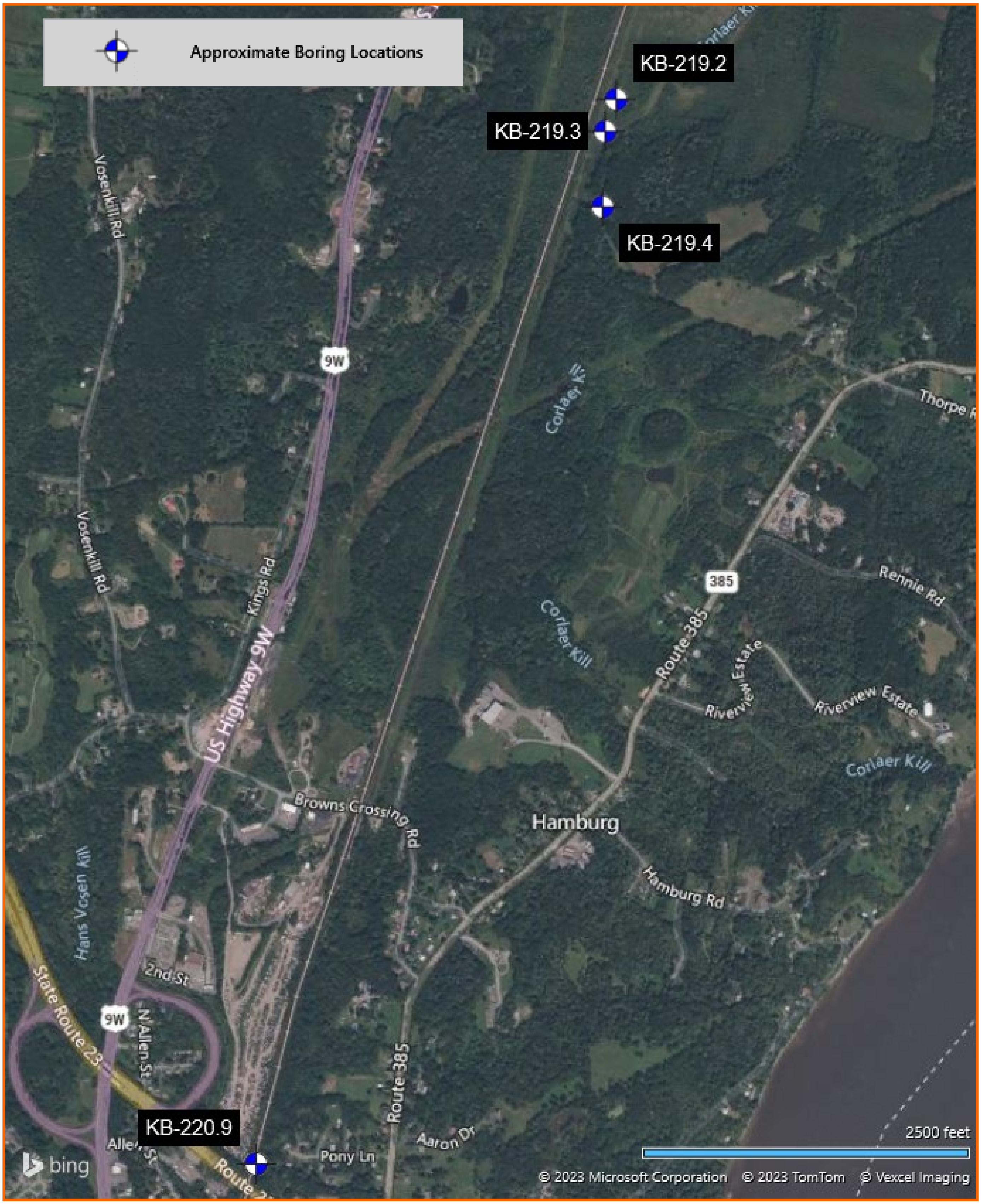


DIAGRAM IS FOR GENERAL LOCATION ONLY, AND IS NOT INTENDED FOR CONSTRUCTION PURPOSES

AERIAL PHOTOGRAPHY PROVIDED BY MICROSOFT BING MAPS

BORING LOG NO. KB-219.2

PROJECT: Phase 4 Borings

SITE: Champlain to Hudson HDD Crossings

CLIENT: Kiewit Engineering (NY) Corp
Lone Tree, CO

LOCATION See Exploration Plan

Latitude: 42.2519° Longitude: -73.8554°

Surface Elev.: 116.683 (Ft.)

DEPTH	Description	ELEVATION (Ft.)	DEPTH (Ft.)	WATER LEVEL OBSERVATIONS	SAMPLE TYPE	RECOVERY (In.)	FIELD TEST RESULTS	WATER CONTENT (%)	ATTERBERG LIMITS LL-PL-PI	PERCENT FINES
0.4	**TOPSOIL**	116.3								
	LEAN CLAY (CL), varved silt and clay, brown, very soft to very stiff				X	12	1-1-2-3 N=3			
					X	18	3-4-6-9 N=10			
			5		X	10	4-4-9-10 N=13	27.5	42-23-19	96
					X	24	11-12-13-14 N=25			
					X	24	11-9-8-8 N=17			
			10		X	24	WH/18"-4			
			15		X	24	WH/12"-3-4 N=3			
20.0		96.7	20							
	ELASTIC SILT (MH), varved silt and clay, gray, very soft				X	24	WH/24"	40.8	50-35-15	99
			25							

Stratification lines are approximate. In-situ, the transition may be gradual.

Hammer Type: Automatic

Advancement Method:
0-10 4" Casing
10'-57' Mud Rotary

Abandonment Method:
Boring backfilled with bentonite grout upon completion

See Exploration and Testing Procedures for a description of field and laboratory procedures used and additional data (If any).

See Supporting Information for explanation of symbols and abbreviations.

Elevations were provided by others.

Notes:

Hammer Efficiency Summary:
Energy Transfer Ratio: 84.7% +/-5.0%
Hammer Efficiency Correction (CE): 1.41
Logged by DOL
WH = Weight of hammer
WR = Weight of rod

WATER LEVEL OBSERVATIONS

No free water encountered

Terracon
30 Corporate Cir Ste 201
Albany, NY

Boring Started: 04-20-2023	Boring Completed: 04-21-2023
Drill Rig: Diedrich D-50	Driller: S. Morey
Project No.: JB215256J	

BORING LOG NO. KB-219.2

PROJECT: Phase 4 Borings

CLIENT: Kiewit Engineering (NY) Corp Lone Tree, CO

SITE: Champlain to Hudson HDD Crossings

LOCATION See Exploration Plan

Latitude: 42.2519° Longitude: -73.8554°

Surface Elev.: 116.683 (Ft.)

DEPTH	Description	ELEVATION (Ft.)	DEPTH (Ft.)	WATER LEVEL OBSERVATIONS	SAMPLE TYPE	RECOVERY (In.)	FIELD TEST RESULTS	WATER CONTENT (%)	ATTERBERG LIMITS LL-PL-PI	PERCENT FINES
	ELASTIC SILT (MH), varved silt and clay, gray, very soft *(continued)*				X	24	WH/24"			
			30		X	24	WR/24"			
			35		X	24	WR/24" 3" Split spoon with ring sampler			
40.0		76.7								
	LEAN CLAY (CL), varved silt and clay, gray, very soft to soft		40		X	24	WR/24"	43.4	41-24-17	94
			45		X	14	WR/12"-4-4 N=4			
			50							

Stratification lines are approximate. In-situ, the transition may be gradual.

Hammer Type: Automatic

Advancement Method:
0-10 4" Casing
10'-57' Mud Rotary

Abandonment Method:
Boring backfilled with bentonite grout upon completion

See Exploration and Testing Procedures for a description of field and laboratory procedures used and additional data (If any).

See Supporting Information for explanation of symbols and abbreviations.

Elevations were provided by others.

Notes:

Hammer Efficiency Summary:
Energy Transfer Ratio: 84.7% +/-5.0%
Hammer Efficiency Correction (CE): 1.41
Logged by DOL
WH = Weight of hammer
WR = Weight of rod

WATER LEVEL OBSERVATIONS

No free water encountered

Terracon
30 Corporate Cir Ste 201
Albany, NY

Boring Started: 04-20-2023	Boring Completed: 04-21-2023
Drill Rig: Diedrich D-50	Driller: S. Morey
Project No.: JB215256J	

BORING LOG NO. KB-219.2

PROJECT: Phase 4 Borings

CLIENT: Kiewit Engineering (NY) Corp Lone Tree, CO

SITE: Champlain to Hudson HDD Crossings

LOCATION See Exploration Plan

Latitude: 42.2519° Longitude: -73.8554°

Surface Elev.: 116.683 (Ft.)

GRAPHIC LOG	DEPTH / ELEVATION (Ft.)	DEPTH (Ft.)	WATER LEVEL OBSERVATIONS	SAMPLE TYPE	RECOVERY (In.)	FIELD TEST RESULTS	WATER CONTENT (%)	ATTERBERG LIMITS LL-PL-PI	PERCENT FINES
	LEAN CLAY (CL), varved silt and clay, gray, very soft to soft *(continued)*			X	8	WH/12"-4-4 N=4			
	55.0 — 61.7	55							
	SANDY SILT WITH GRAVEL (SM), gray, hard, (GLACIAL TILL)			X	10	12-23-15-50/3" N=38			
	56.8 — 59.9								
	Boring Terminated at 56.75 Feet								

Stratification lines are approximate. In-situ, the transition may be gradual.

Hammer Type: Automatic

Advancement Method:
0-10 4" Casing
10'-57' Mud Rotary

Abandonment Method:
Boring backfilled with bentonite grout upon completion

See Exploration and Testing Procedures for a description of field and laboratory procedures used and additional data (If any).

See Supporting Information for explanation of symbols and abbreviations.

Elevations were provided by others.

Notes:

Hammer Efficiency Summary:
Energy Transfer Ratio: 84.7% +/-5.0%
Hammer Efficiency Correction (CE): 1.41
Logged by DOL
WH = Weight of hammer
WR = Weight of rod

WATER LEVEL OBSERVATIONS

No free water encountered

Terracon
30 Corporate Cir Ste 201
Albany, NY

Boring Started: 04-20-2023	Boring Completed: 04-21-2023
Drill Rig: Diedrich D-50	Driller: S. Morey
Project No.: JB215256J	

BORING LOG NO. KB-219.3

PROJECT: Phase 4 Borings

CLIENT: Kiewit Engineering (NY) Corp, Lone Tree, CO

SITE: Champlain to Hudson HDD Crossings

LOCATION See Exploration Plan

Latitude: 42.2512° Longitude: -73.8557°

Surface Elev.: 115.191 (Ft.)

DEPTH	Description	ELEVATION (Ft.)	DEPTH (Ft.)	WATER LEVEL OBSERVATIONS	SAMPLE TYPE	RECOVERY (In.)	FIELD TEST RESULTS	WATER CONTENT (%)	ATTERBERG LIMITS LL-PL-PI	PERCENT FINES
0.4	**TOPSOIL**	114.8								
	FAT CLAY (CH), varved silt and clay, brown, soft to very stiff				X	12	1-2-2-2 N=4			
					X	14	2-4-7-8 N=11			
			5		X	16	6-8-10-11 N=18	29.3	55-29-26	98
					X	20	11-11-12-11 N=23			
					X	22	11-10-10-12 N=20			
			10		X	24	3-4-6-4 N=10			
			15		X	24	2-3-4-4 N=7	39.5	51-26-25	96
20.0		95.2	20							
	LEAN CLAY (CL), varved silt and clay, gray, very soft				X	24	WH/24"			
			25							

Stratification lines are approximate. In-situ, the transition may be gradual.

Hammer Type: Automatic

Advancement Method:
0-10 4" Casing
10'-52' 3" Casing

Abandonment Method:
Boring backfilled with bentonite grout upon completion

See Exploration and Testing Procedures for a description of field and laboratory procedures used and additional data (If any).

See Supporting Information for explanation of symbols and abbreviations.

Elevations were provided by others.

Notes:

Hammer Efficiency Summary:
Energy Transfer Ratio: 84.7% +/-5.0%
Hammer Efficiency Correction (CE): 1.41
Logged by DOL
WH = Weight of hammer

WATER LEVEL OBSERVATIONS

Terracon
30 Corporate Cir Ste 201
Albany, NY

Boring Started: 04-19-2023	Boring Completed: 04-20-2023
Drill Rig: Diedrich D-50	Driller: S. Morey
Project No.: JB215256J	

BORING LOG NO. KB-219.3

PROJECT: Phase 4 Borings

SITE: Champlain to Hudson HDD Crossings

CLIENT: Kiewit Engineering (NY) Corp Lone Tree, CO

LOCATION See Exploration Plan

Latitude: 42.2512° Longitude: -73.8557°

Surface Elev.: 115.191 (Ft.)

DEPTH	Description	ELEVATION (Ft.)	DEPTH (Ft.)	WATER LEVEL OBSERVATIONS	SAMPLE TYPE	RECOVERY (In.)	FIELD TEST RESULTS	WATER CONTENT (%)	ATTERBERG LIMITS LL-PL-PI	PERCENT FINES
	LEAN CLAY (CL), varved silt and clay, gray, very soft *(continued)*				X	24	WH/24"			
			30		X	24	WH/24" 3" Split spoon with ring samplers			
35.0		80.2	35							
	LEAN CLAY WITH SAND (CL), varved silt and clay, gray, very soft to stiff				X	24	WH/24"	23.5	27-18-9	73
			40		X	1	6-6-6-3 N=12			
	gravel noted in tip of sampler									
42.0		73.2								
	SANDY SILT (ML), gray, stiff to hard, (GLACIAL TILL)		45		X	18	15-7-3-50 N=10	15.6		65
			50							

Stratification lines are approximate. In-situ, the transition may be gradual.

Hammer Type: Automatic

Advancement Method:
0-10 4" Casing
10'-52' 3" Casing

Abandonment Method:
Boring backfilled with bentonite grout upon completion

See Exploration and Testing Procedures for a description of field and laboratory procedures used and additional data (If any).

See Supporting Information for explanation of symbols and abbreviations.

Elevations were provided by others.

Notes:

Hammer Efficiency Summary:
Energy Transfer Ratio: 84.7% +/-5.0%
Hammer Efficiency Correction (CE): 1.41
Logged by DOL
WH = Weight of hammer

WATER LEVEL OBSERVATIONS

Terracon
30 Corporate Cir Ste 201
Albany, NY

Boring Started: 04-19-2023	Boring Completed: 04-20-2023
Drill Rig: Diedrich D-50	Driller: S. Morey
Project No.: JB215256J	

BORING LOG NO. KB-219.3

PROJECT: Phase 4 Borings

CLIENT: Kiewit Engineering (NY) Corp
Lone Tree, CO

SITE: Champlain to Hudson HDD Crossings

LOCATION See Exploration Plan

Latitude: 42.2512° Longitude: -73.8557°

Surface Elev.: 115.191 (Ft.)

GRAPHIC LOG	DEPTH / DESCRIPTION / ELEVATION (Ft.)	DEPTH (Ft.)	WATER LEVEL OBSERVATIONS	SAMPLE TYPE	RECOVERY (In.)	FIELD TEST RESULTS	WATER CONTENT (%)	ATTERBERG LIMITS LL-PL-PI	PERCENT FINES
	SANDY SILT (ML), gray, stiff to hard, (GLACIAL TILL) *(continued)*			X	10	16-15-17-18 N=32			
	52.0 ... 63.2								
	Boring Terminated at 52 Feet								

Stratification lines are approximate. In-situ, the transition may be gradual.

Hammer Type: Automatic

Advancement Method:
0-10 4" Casing
10'-52' 3" Casing

Abandonment Method:
Boring backfilled with bentonite grout upon completion

See Exploration and Testing Procedures for a description of field and laboratory procedures used and additional data (If any).

See Supporting Information for explanation of symbols and abbreviations.

Elevations were provided by others.

Notes:

Hammer Efficiency Summary:
Energy Transfer Ratio: 84.7% +/-5.0%
Hammer Efficiency Correction (CE): 1.41
Logged by DOL
WH = Weight of hammer

WATER LEVEL OBSERVATIONS

Terracon
30 Corporate Cir Ste 201
Albany, NY

Boring Started: 04-19-2023	Boring Completed: 04-20-2023
Drill Rig: Diedrich D-50	Driller: S. Morey
Project No.: JB215256J	

Summary of Laboratory Results

BORING ID	Depth (Ft.)	Water Content (%)	Liquid Limit	Plastic Limit	Plasticity Index
KB-206.8	4-6	29.4	50	26	24
KB-206.8	15-17	32.9	40	23	17
KB-206.8	35-37	11.0	17	13	4
KB-207.0	4-6	23.7	42	30	12
KB-207.1	4-6	15.1			
KB-211.4B	4-6	32.8	58	32	26
KB-211.4B	15-17	48.0	55	31	24
KB-211.4B	40-42	36.7	63	32	31
KB-214.4	4-6	33.7	65	33	32
KB-214.4	15-17	37.6	57	29	28
KB-214.4	30-32	49.7	45	30	15
KB-219.2	4-6	27.5	42	23	19
KB-219.2	20-22	40.8	50	35	15
KB-219.2	40-42	43.4	41	24	17
KB-219.3	4-6	29.3	55	29	26
KB-219.3	15-17	39.5	51	26	25
KB-219.3	35-37	23.5	27	18	9
KB-219.3	45-47	15.6			
KB-220.9	4-6	31.0	50	27	23
KB-220.9	20-22	39.6	47	26	21
KB-220.9	45-47	33.6	42	27	15

PROJECT: Phase 4 Borings

SITE: Champlain to Hudson HDD Crossings

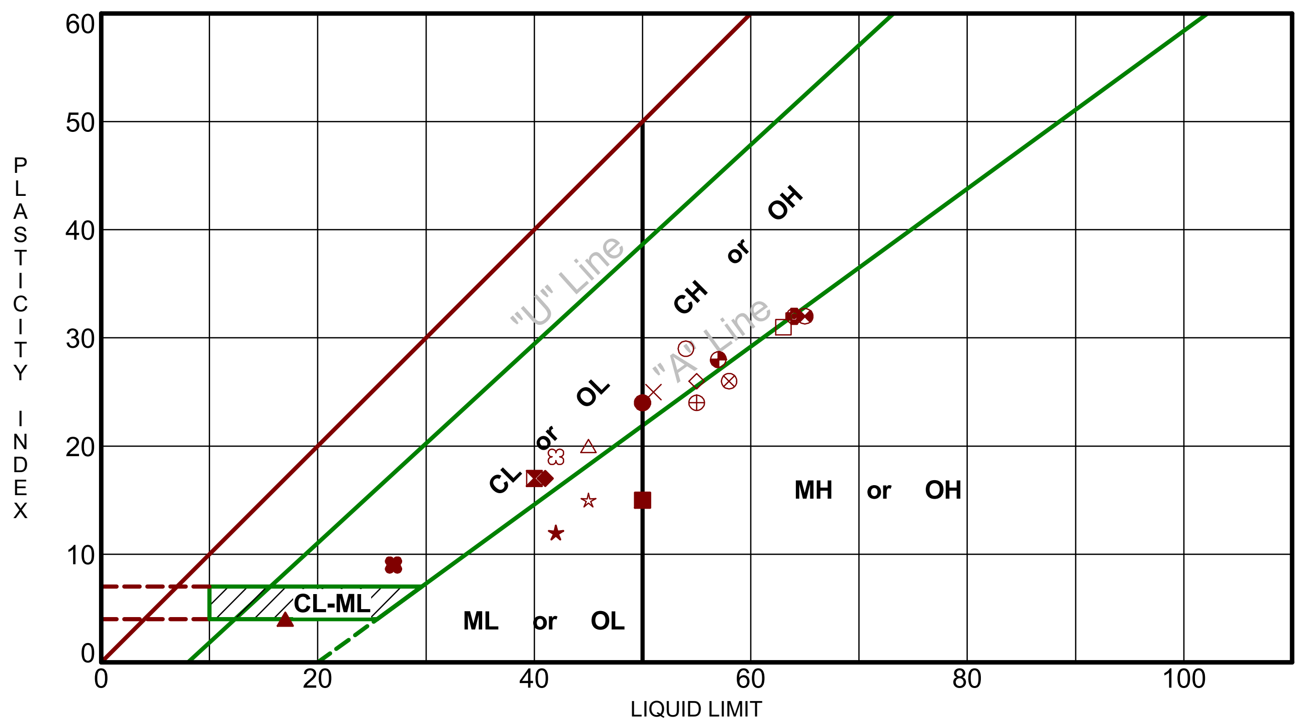
Terracon
30 Corporate Cir Ste 201
Albany, NY

PROJECT NUMBER: JB215256J

CLIENT: Kiewit Engineering (NY) Corp
Lone Tree, CO

ATTERBERG LIMITS RESULTS

ASTM D4318



	Boring ID	Depth (Ft)	LL	PL	PI	Fines	USCS	Description
●	KB-206.8	4 - 6	50	26	24	87.8	CH	FAT CLAY
⊠	KB-206.8	15 - 17	40	23	17	99.4	CL	LEAN CLAY
▲	KB-206.8	35 - 37	17	13	4	37.5	SC-SM	SILTY, CLAYEY SAND with GRAVEL
★	KB-207.0	4 - 6	42	30	12	86.9	ML	SILT
⊙	KB-209.7	4 - 6	64	32	32	100.0	MH	ELASTIC SILT
✿	KB-209.7	15 - 17	64	32	32	100.0	MH	ELASTIC SILT
○	KB-209.7	25 - 27	54	25	29	100.0	CH	FAT CLAY
△	KB-209.7	40 - 42	45	25	20	100.0	CL	LEAN CLAY
⊗	KB-211.4B	4 - 6	58	32	26	53.8	MH	SANDY ELASTIC SILT
⊕	KB-211.4B	15 - 17	55	31	24	82.0	MH	ELASTIC SILT with SAND
□	KB-211.4B	40 - 42	63	32	31	96.7	MH	ELASTIC SILT
◉	KB-214.4	4 - 6	65	33	32	84.2	MH	ELASTIC SILT with SAND
◕	KB-214.4	15 - 17	57	29	28	94.7	CH	FAT CLAY
☆	KB-214.4	30 - 32	45	30	15	93.2	ML	SILT
❀	KB-219.2	4 - 6	42	23	19	96.5	CL	LEAN CLAY
■	KB-219.2	20 - 22	50	35	15	99.4	MH	ELASTIC SILT
◆	KB-219.2	40 - 42	41	24	17	93.9	CL	LEAN CLAY
◇	KB-219.3	4 - 6	55	29	26	98.3	CH	FAT CLAY
×	KB-219.3	15 - 17	51	26	25	95.6	CH	FAT CLAY
✖	KB-219.3	35 - 37	27	18	9	73.3	CL	LEAN CLAY with SAND

PROJECT: Phase 4 Borings

SITE: Champlain to Hudson HDD Crossings

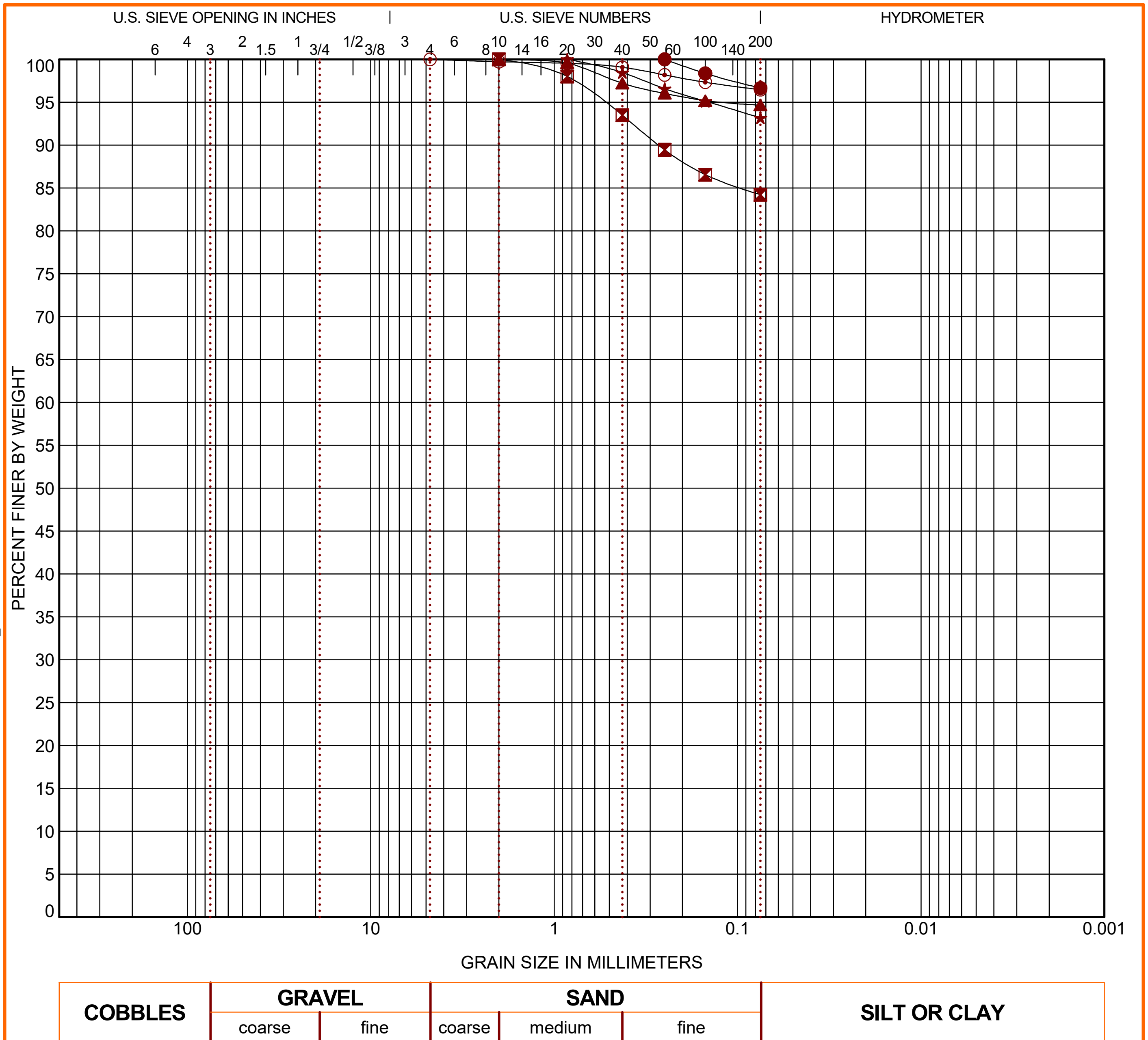
Terracon
30 Corporate Cir Ste 201
Albany, NY

PROJECT NUMBER: JB215256J

CLIENT: Kiewit Engineering (NY) Corp
Lone Tree, CO

GRAIN SIZE DISTRIBUTION

ASTM D422 / ASTM C136



	Boring ID	Depth (Ft)	USCS Classification	WC (%)	LL	PL	PI	Cc	Cu
●	KB-211.4B	40 - 42	ELASTIC SILT (MH)	36.7	63	32	31		
⊠	KB-214.4	4 - 6	ELASTIC SILT with SAND (MH)	33.7	65	33	32		
▲	KB-214.4	15 - 17	FAT CLAY (CH)	37.6	57	29	28		
★	KB-214.4	30 - 32	SILT (ML)	49.7	45	30	15		
⊙	KB-219.2	4 - 6	LEAN CLAY (CL)	27.5	42	23	19		

	Boring ID	Depth (Ft)	D_{100}	D_{60}	D_{30}	D_{10}	%Cobbles	%Gravel	%Sand	%Silt	%Fines	%Clay
●	KB-211.4B	40 - 42	0.25				0.0	0.0	3.3		96.7	
⊠	KB-214.4	4 - 6	2				0.0	0.0	15.8		84.2	
▲	KB-214.4	15 - 17	2				0.0	0.0	5.3		94.7	
★	KB-214.4	30 - 32	0.85				0.0	0.0	6.8		93.2	
⊙	KB-219.2	4 - 6	4.75				0.0	0.0	3.5		96.5	

PROJECT: Phase 4 Borings

SITE: Champlain to Hudson HDD Crossings

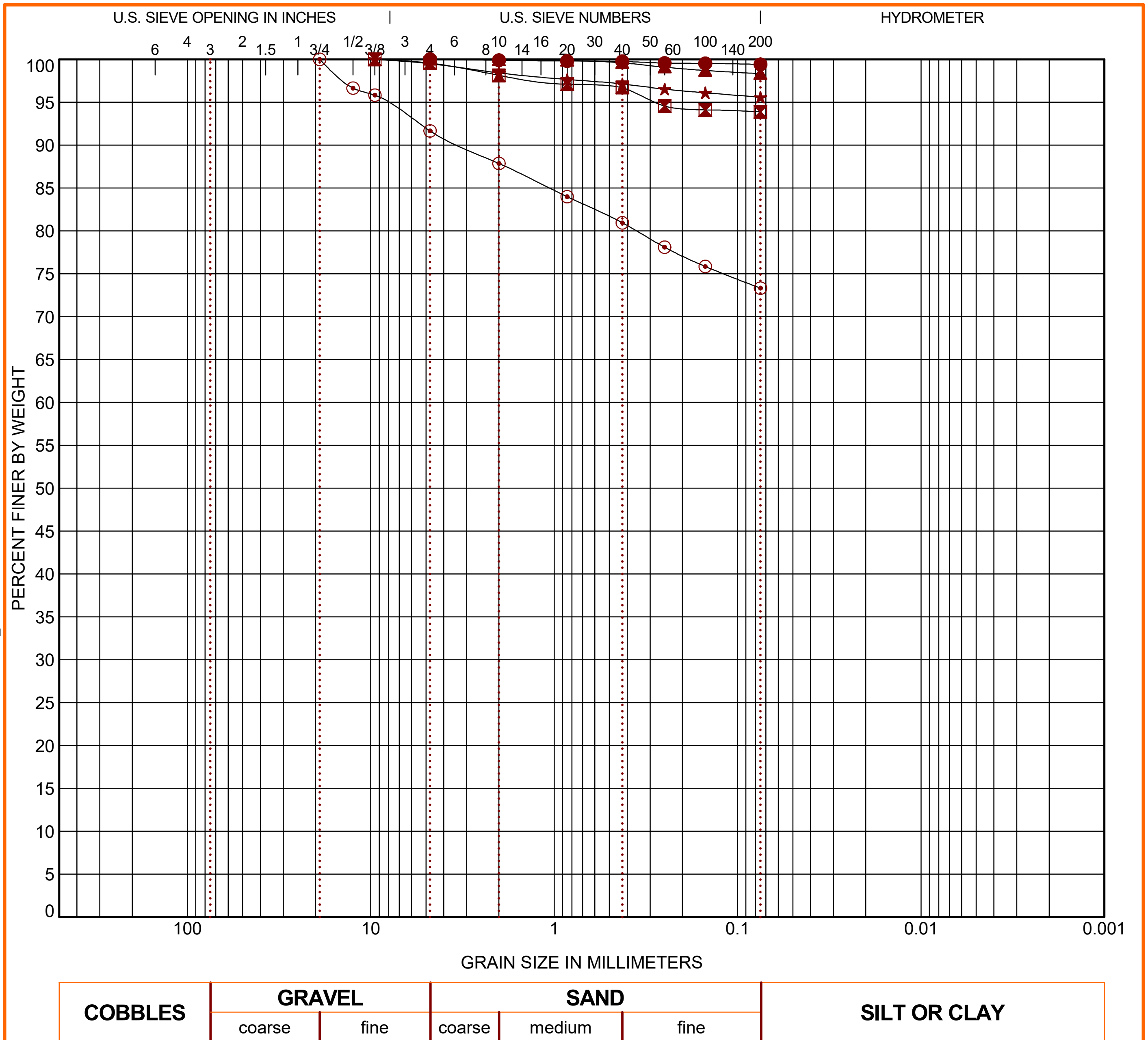
Terracon
30 Corporate Cir Ste 201
Albany, NY

PROJECT NUMBER: JB215256J

CLIENT: Kiewit Engineering (NY) Corp
Lone Tree, CO

GRAIN SIZE DISTRIBUTION

ASTM D422 / ASTM C136



Boring ID		Depth (Ft)	USCS Classification	WC (%)	LL	PL	PI	Cc	Cu
●	KB-219.2	20 - 22	ELASTIC SILT (MH)	40.8	50	35	15		
⧗	KB-219.2	40 - 42	LEAN CLAY (CL)	43.4	41	24	17		
▲	KB-219.3	4 - 6	FAT CLAY (CH)	29.3	55	29	26		
★	KB-219.3	15 - 17	FAT CLAY (CH)	39.5	51	26	25		
⊙	KB-219.3	35 - 37	LEAN CLAY with SAND (CL)	23.5	27	18	9		

Boring ID		Depth (Ft)	D_{100}	D_{60}	D_{30}	D_{10}	%Cobbles	%Gravel	%Sand	%Silt	%Fines	%Clay
●	KB-219.2	20 - 22	4.75				0.0	0.0	0.6		99.4	
⧗	KB-219.2	40 - 42	9.5				0.0	0.4	5.7		93.9	
▲	KB-219.3	4 - 6	4.75				0.0	0.0	1.7		98.3	
★	KB-219.3	15 - 17	9.5				0.0	0.5	3.9		95.6	
⊙	KB-219.3	35 - 37	19				0.0	8.3	18.3		73.3	

PROJECT: Phase 4 Borings

SITE: Champlain to Hudson HDD Crossings

Terracon
30 Corporate Cir Ste 201
Albany, NY

PROJECT NUMBER: JB215256J

CLIENT: Kiewit Engineering (NY) Corp
Lone Tree, CO

Appendix C

Calculation Package

Defining Parameters of Horizontal Directional Drilling :

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

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

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

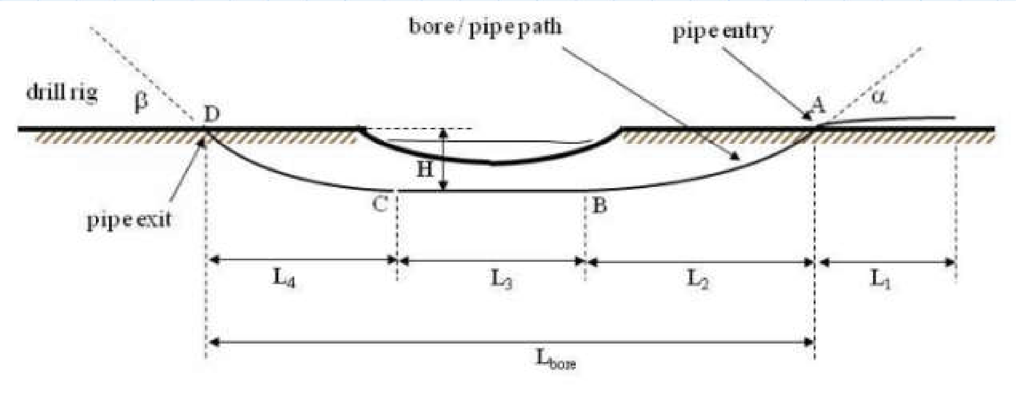


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 8\ °$ $\alpha_{in} := \alpha = 0.1396\ rad$ Borehole entry angle (degrees, radians)
$\beta := 8\ °$ $\beta_{exit} := \beta = 0.1396\ rad$ Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$ Final reamed bore diameter
$H_{max} := 40.0\ ft$ Max depth of bore hole to final reamed bore diameter

$H_{max1} := H_{max} + \frac{D_r}{2} = 40.75\ ft$ Max depth to bore hole springline from ground surface

$L_{total} := 551.2\ ft$ Total length of HDD crossing
$L_1 := 150\ ft$ Assumed pipe drag on surface, See Illustration 1

$L_2 := 203.7\ ft$ Horizontal length to achieve depth - provided by Contractor, See Illustration 1

$L_3 := 149.1\ ft$ Straight horizontal section
$L_4 := 198.4\ ft$ Horizontal distance to rise to surface, See Illustration 1

$H := 18.0\ ft$ Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1

$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 90\ pcf$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.4$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

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

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

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

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

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

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

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

B1.2 - Upward Buoyant Force:

Effective weight

$$w_b := \left(\frac{\pi \cdot \left(D_1^{\,2} + D_2^{\,2}\right)}{4}\right) \rho_w \cdot \gamma_b - w_a = 51.2\ \mathit{plf}$$

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

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

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 589\ \mathit{lbf}$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}}\left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 6192\ \mathit{lbf}$$

Pullback force increase with depth

B1.6 - Pullback Force Point C:

$$T_c := T_b + \left(v_b \cdot w_b \cdot L_3\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 8352\ \mathit{lbf}$$

B1.7 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_c + v_b \cdot \left|w_b\right| \cdot L_4 - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 11711\ \mathit{lbf}$$

B1.8 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_c, T_d\right) + \Delta T = 12508\ \mathit{lbf}$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi \cdot D_1^{\,2}\right)}{4}\right) \cdot \rho_w \cdot \left(\gamma_b - \gamma_c \cdot \left(1 - \left(\frac{2}{DR_1}\right)\right)^2\right) - w_a = 24.6\ \mathit{plf}$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 589\ \mathit{lbf}$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot |w_{bfilled}| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 3392 \ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C:

$$T_{cfilled} := T_{bfilled} + (v_b \cdot |w_{bfilled}| \cdot L_3) - e^{(v_b \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 4363 \ lbf$$

B2.5 - Pullback Force at D:

$$T_{dfilled} := e^{(v_b \cdot \beta_{exit})} \cdot \left(T_{cfilled} + v_b \cdot |w_{bfilled}| \cdot L_4 - e^{(v_a \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{(v_a \cdot \alpha_{in})}\right)\right) = 5904 \ lbf$$

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

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{cfilled}, T_{dfilled}\right) = 5904 \ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

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

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

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 12022 \ lbf$$ Pullback forces acting on Pipe 1 (Empty)

$$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 485 \ lbf$$ Pullback forces acting on Pipe 2 (Empty)

$$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 5674 \ lbf$$ Pullback forces acting on Pipe 1 (Ballast)

$$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 229 \ lbf$$ Pullback forces acting on Pipe 2 (Ballast)

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

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

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

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

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

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

$H_w := 10.3 \cdot ft$ — Depth of the bore below groundwater elevation

$H_c := 40.0\ ft$ — Vertical separation distance between critical structure and pipe (Route 9)

$\gamma := 125\ pcf$ — Assumed unit weight silty sand (B-198.9-1 and SC-1A, ~3+00)

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

$\gamma' := \gamma - \gamma_w = 62.6\ pcf$ — Effective unit weight

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

$\phi := 34\ deg$ — Assumed friction Angle (KIE)

$c := 0\ psf = 0\ psi$ — Assumed cohesion of encountered material

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

$R_{pmax} := \frac{2}{3} \cdot H_c = 27\ ft$ — Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := \left(\left(\gamma \cdot \left(H_c - H_w\right)\right) + \gamma' \cdot H_w\right) = 30.3\ psi$ — Initial effective stress (conservative assume all buoyant)

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

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

$E_s := 7\ \frac{N}{mm^2} = 1015\ psi$

Assumed modulus of elasticity (silty sand)

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

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

$\nu_s := 0.25$ Poissions ratio of material encountered

$$G := \frac{E_s}{2\left(1+\nu_s\right)} = 406\ psi$$ Shear modulus of soil

$$Q := \frac{\left(\sigma'_0 \cdot \sin(\phi)\right) + \left(c \cdot \cos(\phi)\right)}{G} = 0.0417$$ Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot \left(1+\sin(\phi)\right) + c \cdot \cos(\phi) = 47.2\ psi$$ Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + \left(c \cdot \cot(\phi)\right)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot \cot(\phi) = 147.5\ psi$$ Maximum allowable effective mud pressure (Delft Equation)

$$p_{max} := u + p'_{max} = 151.9\ psi$$ Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

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

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

$h := 18.04\ ft$ Elevation difference between level of bore hole front and structure point of mud flow

$\gamma_m = 90\ pcf$ Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 11.3\ psi$ Minimum required mud pressure to overcome differntial head

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

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

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

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

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

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

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 12.2\ psi$ Minimum required mud pressure

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

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

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

$H_c := H_{max} = 40\ ft$ — Depth of cover

$\phi = 34\ deg$ — Friction angle of soil

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

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

$\gamma = 125\ pcf$ — Unit weight of soil, assumed

$$k := \frac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)\right)}{2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)} = 0.079$$

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

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 1\ psi \quad P_E = 199\ psf$ — Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

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

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

Variable in earth load deflection equation

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

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

D1.3 Earth Load Deflection (Long Term)

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

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

Variable in earth load deflection equation

$$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 0.4\%$$

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

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

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

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

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

$\gamma_m = 90\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

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

$$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.1\%$$

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

D2.1 Buoyant Deflection (Long Term)

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

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

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

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

D4.1 - Net Short Term

$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 0.2\%$

Percent ring deflection in short term analysis

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

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 0.4\%$

Percent ring deflection in long term analysis (50 years)

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

D5 - Unconstrained Ring Buckling

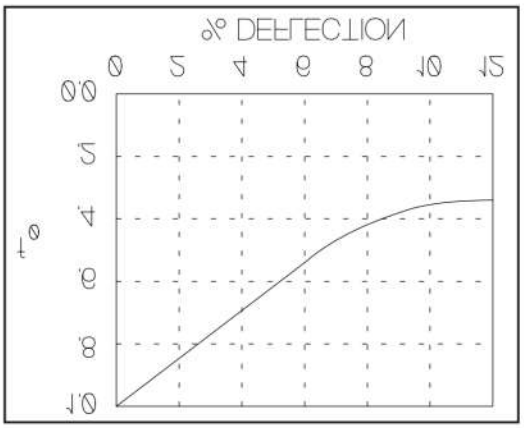
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

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

$N := 2.0$ — Factor of Safety

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

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



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

$f_{o\_short} := 0.98$

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

Allowable unconstrained buckling pressure

$H = 18\ ft$ — Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 11.25\ psi$ — Pressure of drilling slurry

$P_{net} := P_{mud} = 11.25\ psi$ — Net external loading with open borehole

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

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

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

$N := 2.0$ — Factor of Safety

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

$E_{long} = 28200\ psi$

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

$f_{o\_long} := 0.45$

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

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

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 4.463\ psi$

Groundwater head pressure

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

Net external loading with open borehole

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

References

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

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

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

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

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

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

91.A

Defining Parameters of Horizontal Directional Drilling :

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

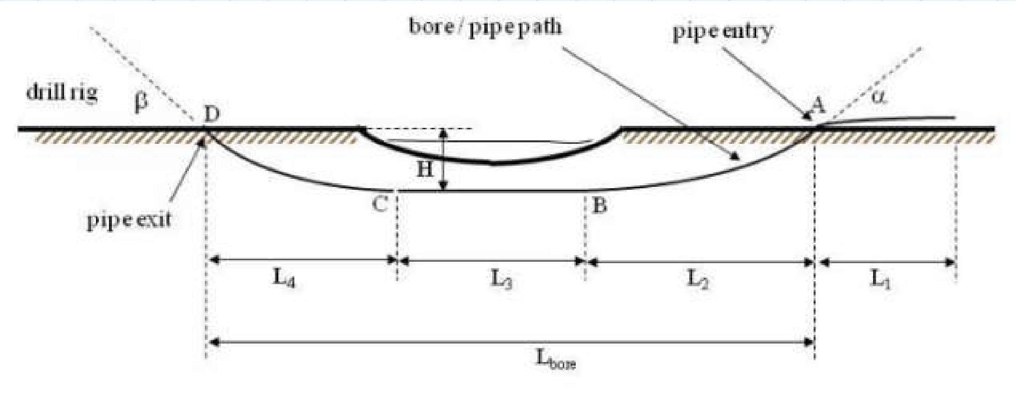


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 8\ °$ $\alpha_{in} := \alpha = 0.1396\ rad$	Borehole entry angle (degrees, radians)
$\beta := 10\ °$ $\beta_{exit} := \beta = 0.1745\ rad$	Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$	Final reamed bore diameter
$H_{max} := 23.2\ ft$	Max depth of bore hole to final reamed bore diameter
$H_{max1} := H_{max} + \frac{D_r}{2} = 23.95\ ft$	Max depth to bore hole springline from ground surface
$L_{total} := 1610.6\ ft$	Total length of HDD crossing
$L_1 := 150\ ft$	Assumed pipe drag on surface, See Illustration 1
$L_2 := 218.9\ ft$	Horizontal length to achieve depth - provided by Contractor, See Illustration 1
$L_3 := 1160\ ft$	Straight horizontal section
$L_4 := 231.7\ ft$	Horizontal distance to rise to surface, See Illustration 1
$H := 26.9\ ft$	Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1

$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 67\ pcf = 9\ \frac{lbf}{gal}$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.1$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

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

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

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

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

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

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

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

Effective weight

B1.2 - Upward Buoyant Force:

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

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

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

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot (L_1 + L_2 + L_3 + L_4)\right) = 1480\ lbf$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}}\left(T_a + v_b \cdot |w_b| \cdot L_2 + w_b \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 5071\ lbf$$

Pullback force increase with depth

B1.6 - Pullback Force Point C:

$$T_c := T_b + (v_b \cdot w_b \cdot L_3) - e^{(v_b \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 16584\ lbf$$

B1.7 - Pullback Force at D:

$$T_d := e^{(v_b \cdot \beta_{exit})} \cdot \left(T_c + v_b \cdot |w_b| \cdot L_4 - e^{(v_a \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{(v_a \cdot \alpha_{in})}\right)\right) = 19905\ lbf$$

B1.8 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max(T_a, T_b, T_c, T_d) + \Delta T = 20701\ lbf$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

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

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot (L_1 + L_2 + L_3 + L_4)\right) = 1480\ lbf$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 2675\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C:

$$T_{cfilled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_3\right) - e^{(v_b \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 5191\ lbf$$

B2.5 - Pullback Force at D:

$$T_{dfilled} := e^{(v_b \cdot \beta_{exit})} \cdot \left(T_{cfilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{(v_a \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{(v_a \cdot \alpha_{in})}\right)\right) = 6005\ lbf$$

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

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{cfilled}, T_{dfilled}\right) = 6005\ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

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

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

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 19898\ lbf$$ Pullback forces acting on Pipe 1 (Empty)

$$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 803\ lbf$$ Pullback forces acting on Pipe 2 (Empty)

$$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 5772\ lbf$$ Pullback forces acting on Pipe 1 (Ballast)

$$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 233\ lbf$$ Pullback forces acting on Pipe 2 (Ballast)

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

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

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

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

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

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

$H_w := 19.7 \cdot ft$ — Depth of the bore below groundwater elevation

$H_c := 25.1\ ft$ — Vertical separation distance between critical structure and pipe (Old Ravena Rd., ~8+00)

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

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

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

$u := \gamma_w \cdot H_w = 9\ psi$ — Initial pore water pressure

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

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

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

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

$\sigma'_0 := \left(\left(\gamma \cdot \left(H_c - H_w\right)\right) + \gamma' \cdot H_w\right) = 9\ psi$ — Initial effective stress

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

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

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

Assumed modulus of elasticity

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

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

$\nu_s := 0.5$

Poissions ratio of material encountered

$$G := \frac{E_s}{2\left(1+\nu_s\right)} = 97\ psi$$

Shear modulus of soil

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

Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot (1+\sin(\phi)) + c \cdot \cos(\phi) = 12\ psi$$

Mud pressure at which the first plastic deformation takes place

$$p'_{max1} := \left(p'_f + (c \cdot 0)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot 0 = 12\ psi$$

$$p'_{max2} := p'_f + c = 15.1\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$$p_{max} := u + p'_{max2} = 23.7\ psi$$

Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

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

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

$h := 26.9\ ft$ — Elevation difference between level of bore hole front and exit point of mud flow

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

$p_1 := \gamma_m \cdot h = 12.5\ psi$ — Minimum required mud pressure to overcome differntial head

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

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

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

$$v := \frac{Q_f}{0.785\left(D_r^{\,2} - \left(D_1^{\,2} + D_2^{\,2}\right)\right)} = 24.2\ \frac{ft}{min}$$

Computed mud flow velocity

$L_{structure} := 800\ ft$

Length to sturcture

$$p_2 := L_{structure} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2}\right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)}\right)\right) = 2.4\ psi$$

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 14.9\ psi$

Minimum required mud pressure

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

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

$H_c := H_{max} = 23.2\ ft$ — Depth of cover

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

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

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

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

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

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

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 6\ psi \qquad P_E = 872\ psf$ — Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

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

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

Variable in earth load deflection equation

$$\Delta y_{ELD\_short} := \frac{0.0125 \cdot P_E}{k_{short}} = 0.8\%$$

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

D1.3 Earth Load Deflection (Long Term)

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

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

Variable in earth load deflection equation

$$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 1.6\%$$

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

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

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

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

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

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

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

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

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

D2.1 Buoyant Deflection (Long Term)

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

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

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

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

D4.1 - Net Short Term

$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 0.9\%$

Percent ring deflection in short term analysis

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

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 1.6\%$

Percent ring deflection in long term analysis (50 years)

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

D5 - Unconstrained Ring Buckling

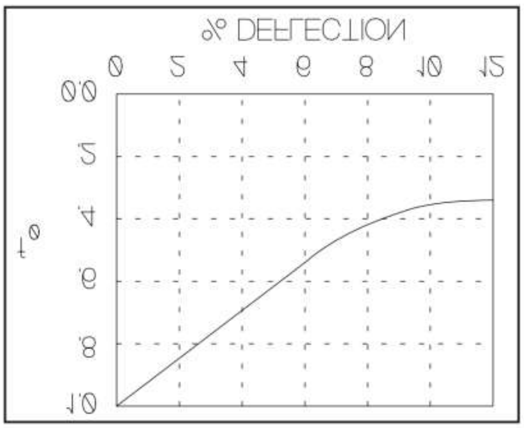
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

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

$N := 2.0$ — Factor of Safety

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

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



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

$f_{o\_short} := 0.98$

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

Allowable unconstrained buckling pressure

$H = 26.9\ ft$ — Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 12.52\ psi$ — Pressure of drilling slurry

$P_{net} := P_{mud} = 12.52\ psi$ — Net external loading with open borehole

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

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

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

$N := 2.0$ — Factor of Safety

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

$E_{long} = 28200\ psi$

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

$f_{o\_long} := 0.45$

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

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

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 8.5\ psi$

Groundwater head pressure

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

Net external loading with open borehole

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

References

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

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

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

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

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

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

92 & 92.A

Defining Parameters of Horizontal Directional Drilling :

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

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

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

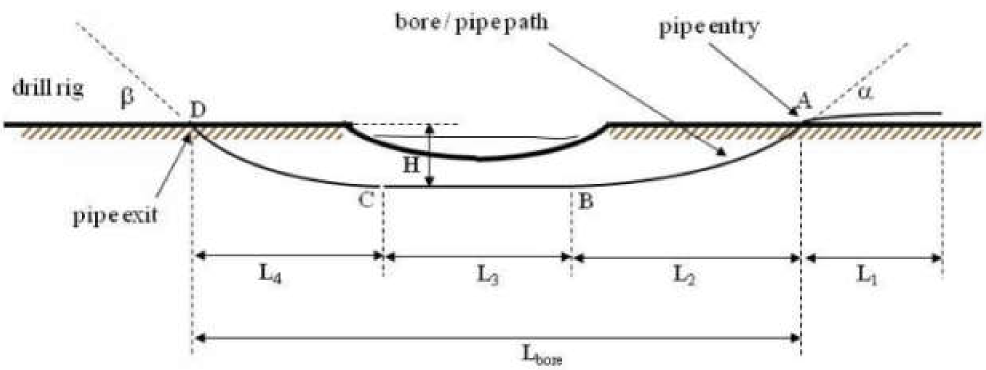


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 12\ °$ $\alpha_{in} := \alpha = 0.2094\ rad$ Borehole entry angle (degrees, radians)
$\beta := 12\ °$ $\beta_{exit} := \beta = 0.2094\ rad$ Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$ Final reamed bore diameter
$H_{max} := 147.6\ ft$ Max depth of bore hole to final reamed bore diameter

$H_{max1} := H_{max} + \frac{D_r}{2} = 148.35\ ft$ Max depth to bore hole springline from ground surface

$L_{total} := 2092\ ft$ Total length of HDD crossing
$L_1 := 150\ ft$ Assumed pipe drag on surface, See Illustration 1

$L_2 := 702.5\ ft$ Horizontal length to achieve depth - provided by Contractor, See Illustration 1

$L_3 := 1058\ ft$ Straight horizontal section
$L_4 := 331\ ft$ Horizontal distance to rise to surface, See Illustration 1

$H := 50\ ft$ Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1

$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 90\ pcf$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.4$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

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

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

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

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

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

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

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

Effective weight

B1.2 - Upward Buoyant Force:

$$w_b := \left(\frac{\pi \cdot \left(D_1^{\,2} + D_2^{\,2}\right)}{4}\right) \rho_w \cdot \gamma_b - w_a = 51.2\ \mathbf{plf}$$

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

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

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 1897\ \mathbf{lbf}$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}} \left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 22193\ \mathbf{lbf}$$

Pullback force increase with depth

B1.6 - Pullback Force Point C:

$$T_c := T_b + \left(v_b \cdot w_b \cdot L_3\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 37494\ \mathbf{lbf}$$

B1.7 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_c + v_b \cdot \left|w_b\right| \cdot L_4 - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 45035\ \mathbf{lbf}$$

B1.8 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_c, T_d\right) + \Delta T = 45831\ \mathbf{lbf}$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi \cdot D_1^{\,2}\right)}{4}\right) \cdot \rho_w \cdot \left(\gamma_b - \gamma_c \cdot \left(1 - \left(\frac{2}{DR_1}\right)\right)^2\right) - w_a = 24.6\ \mathbf{plf}$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 1897\ \mathbf{lbf}$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot |w_{bfilled}| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 12058\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C:

$$T_{cfilled} := T_{bfilled} + \left(v_b \cdot |w_{bfilled}| \cdot L_3\right) - e^{(v_b \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 18927\ lbf$$

B2.5 - Pullback Force at D:

$$T_{dfilled} := e^{(v_b \cdot \beta_{exit})} \cdot \left(T_{cfilled} + v_b \cdot |w_{bfilled}| \cdot L_4 - e^{(v_a \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{(v_a \cdot \alpha_{in})}\right)\right) = 22456\ lbf$$

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

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{cfilled}, T_{dfilled}\right) = 22456\ lbf$$ Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

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

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

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 44053\ lbf$$ Pullback forces acting on Pipe 1 (Empty)

$$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 1778\ lbf$$ Pullback forces acting on Pipe 2 (Empty)

$$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 21585\ lbf$$ Pullback forces acting on Pipe 1 (Ballast)

$$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 871\ lbf$$ Pullback forces acting on Pipe 2 (Ballast)

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

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

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

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

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

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

The first two checks indicate pullback will not be sufficient w/o ballast - therefore, KUE recommends ballast for HDD C1 & C2 (i.e. last two checks are sufficient w/ ballast).

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

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

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

- Diameter/radius based on the most critical stage (i.e. during pilot tube)

-Asssume cot(0 deg) = 0 theoretically infinite)

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

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

$H_w := 18.9 \cdot ft$ — Depth of the bore below groundwater El.

$H_c := 18.9\ ft$ — Vertical separation distance between critical structure and pipe (S-14)

$\gamma := 100\ pcf$ — Assumed unit weight soft clay/silt (CL-ML)

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

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

$u := \gamma_w \cdot H_w = 8.2\ psi$ — Initial pore water pressure

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

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

$R_0 := \frac{D_0}{2} = 4.75\ in$ — Initial radius of the borehole

$R_{pmax} := \frac{1}{2} \cdot H_c = 9.5\ ft$ — Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := ((\gamma \cdot (H_c - H_w)) + \gamma' \cdot H_w) = 4.9\ psi$ — Initial effective stress

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

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

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

Assumed modulus of elasticity

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

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

$\nu_s := 0.4$

Poissions ratio of material encountered

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

Shear modulus of soil

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

Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot (1+\sin(\phi)) + c \cdot \cos(\phi) = 8.1\ psi$$

Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + (c \cdot Q)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot 0 = 8.1\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$$p_{max} := u + p'_{max} = 16.3\ psi$$

Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

$h := 106.5\ ft$

Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 90\ pcf$

Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 66.6\ psi$

Minimum required mud pressure to overcome differntial head

$Q_f := 200\ gpm$

Assumed mud flow rate

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

Assumed yield point of mud per 100 square feet

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

Assumed plastic viscosity of mud

$D_{PT} := 5\ in$

Pilot tube diameter

$D_0 := 9.5\ in$

Initial borehole diameter for pilot tube

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

Computed mud flow velocity

$v = 1.3 \frac{ft}{s}$ Computed mud flow velocity (check on units)

$L_{structure} := 1825\ ft$ Length to sturcture

$\left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2}\right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)}\right)\right) = 0.003 \frac{psi}{ft}$ Check mud pressure units

$p_2 := L_{structure} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2}\right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)}\right)\right) = 5.5\ psi$

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 72\ psi$ Minimum required mud pressure

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

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

$H_c := H_{max} = 147.6\ ft$ — Depth of cover

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

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

$K := \tan\left(45 - \frac{\phi}{2}\right)^2 = 2.624$ — Earth pressure coefficient

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

Can't divide by 0 ~ assume friction angle (ϕ) = 1x10^-2

$$k := \frac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot 1 \cdot 10^{-2}\right)}{2 \cdot \frac{K \cdot H_c}{B} \cdot 1 \cdot 10^{-2}} = 0.193$$

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

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 7\ psi \quad P_E = 1069\ psf$ — Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

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

$k := 1$

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

Variable in earth load deflection equation

$$\Delta y_{ELD\_short} := \frac{0.0125 \cdot P_E}{k_{short}} = 1.0\%$$

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

D1.3 Earth Load Deflection (Long Term)

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

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

Variable in earth load deflection equation

$$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 2.0\%$$

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

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

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

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

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

$\gamma_m = 90\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

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

$$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.1\%$$

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

D2.1 Buoyant Deflection (Long Term)

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

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

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

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

D4.1 - Net Short Term

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

Percent ring deflection in short term analysis

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

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 2.0\%$

Percent ring deflection in long term analysis (50 years)

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

D5 - Unconstrained Ring Buckling

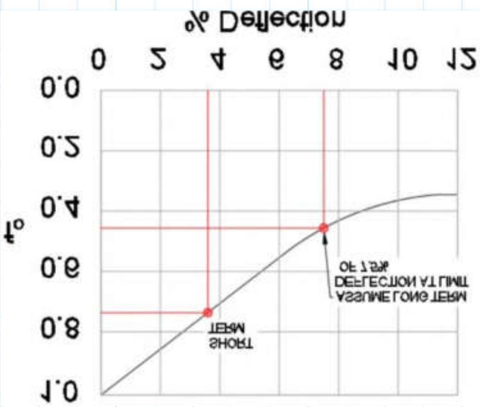
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

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

$N := 2.0$ Factor of Safety

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

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



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

$f_{o\_short} := 0.75$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1 - \mu_{short}^2}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_short}}{N} = 96\ psi$$

Allowable unconstrained buckling pressure

$H = 50\ ft$ Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 31.25\ psi$ Pressure of drilling slurry

$P_{net} := P_{mud} = 31.25\ psi$ Net external loading with open borehole

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

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

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

$N := 2.0$ Factor of Safety

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

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

$f_{o\_long} := 0.45$ Ovality compensation factor, Figure 3 (PPI Chp. 12). Use deflection limit calculated in Section D4.2

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

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 8.19\ psi$ Groundwater head pressure

$P_{net} := P_{GW}$ Net external loading with open borehole

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

References

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

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

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

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

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

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

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Defining Parameters of Horizontal Directional Drilling :

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

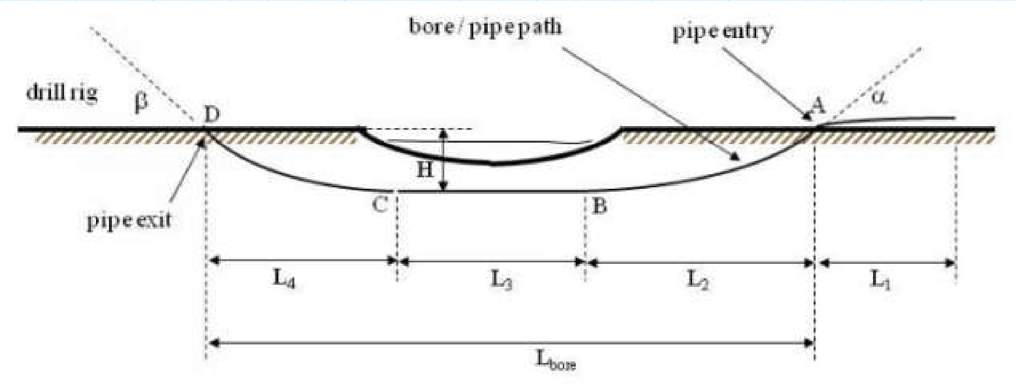


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 9\ °$ $\alpha_{in} := \alpha = 0.1571\ rad$	Borehole entry angle (degrees, radians)
$\beta := 10\ °$ $\beta_{exit} := \beta = 0.1745\ rad$	Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$	Final reamed bore diameter
$H_{max} := 27.3\ ft$	Max depth of bore hole to final reamed bore diameter
$H_{max1} := H_{max} + \frac{D_r}{2} = 28.05\ ft$	Max depth to bore hole springline from ground surface
$L_{total} := 1666.6\ ft$	Total length of HDD crossing
$L_1 := 150\ ft$	Assumed pipe drag on surface, See Illustration 1
$L_2 := 221.8\ ft$	Horizontal length to achieve depth - provided by Contractor, See Illustration 1
$L_3 := 1249\ ft$	Straight horizontal section
$L_4 := 195.8\ ft$	Horizontal distance to rise to surface, See Illustration 1
$H := 16.8\ ft$	Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1

$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 90\ pcf$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.4$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

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

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

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

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

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

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

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

Effective weight

B1.2 - Upward Buoyant Force:

$$w_b := \left(\frac{\pi \cdot \left(D_1^{\,2} + D_2^{\,2}\right)}{4}\right) \rho_w \cdot \gamma_b - w_a = 51.2\ plf$$

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

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

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 1529\ lbf$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}} \left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 6445\ lbf$$

Pullback force increase with depth

B1.6 - Pullback Force Point C:

$$T_c := T_b + \left(v_b \cdot w_b \cdot L_3\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 24530\ lbf$$

B1.7 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_c + v_b \cdot \left|w_b\right| \cdot L_4 - w_b \cdot H_{max} - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 27369\ lbf$$

B1.8 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_c, T_d\right) + \Delta T = 28165\ lbf$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi \cdot D_1^{\,2}\right)}{4}\right) \cdot \rho_w \cdot \left(\gamma_b - \gamma_c \cdot \left(1 - \left(\frac{2}{DR_1}\right)\right)^2\right) - w_a = 24.6\ plf$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 1529\ lbf$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 4223 \ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C:

$$T_{cfilled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_3\right) - e^{(v_b \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 12356 \ lbf$$

B2.5 - Pullback Force at D:

$$T_{dfilled} := e^{(v_b \cdot \beta_{exit})} \cdot \left(T_{cfilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{(v_a \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{(v_a \cdot \alpha_{in})}\right)\right) = 14370 \ lbf$$

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

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{cfilled}, T_{dfilled}\right) = 14370 \ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

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

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

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 27073 \ lbf$$ Pullback forces acting on Pipe 1 (Empty)

$$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 1093 \ lbf$$ Pullback forces acting on Pipe 2 (Empty)

$$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 13812 \ lbf$$ Pullback forces acting on Pipe 1 (Ballast)

$$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 557 \ lbf$$ Pullback forces acting on Pipe 2 (Ballast)

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

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

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

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

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

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

- Diameter/radius based on the most critical stage (i.e. during pilot tube)

-Asssume cot(0 deg) = 0 theoretically infinite)

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

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

$H_w := 17.4 \cdot ft$ Depth of the bore below groundwater elevation

$H_c := 17.4\ ft$ Vertical separation distance between critical structure and pipe (wetlands; ~Sta 5+50)

$\gamma := 110\ pcf$ Assumed unit weight med stiff to stiff silty clay & silt (ML, CL-ML)

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

$\gamma' := \gamma - \gamma_w = 47.6\ pcf$ Effective unit weight

$u := \gamma_w \cdot H_w = 7.5\ psi$ Initial pore water pressure

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

$c := 800\ psf = 5.56\ psi$ Assumed cohesion of encountered material

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

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

$\sigma'_0 := \left(\left(\gamma \cdot \left(H_c - H_w\right)\right) + \gamma' \cdot H_w\right) = 5.8\ psi$ Initial effective stress

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

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

$E_s := 15\ \dfrac{N}{mm^2} = 2176\ psi$

Assumed modulus of elasticity

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

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

$\nu_s := 0.4$

Poissions ratio of material encountered

$$G := \frac{E_s}{2\left(1+\nu_s\right)} = 777\ psi$$

Shear modulus of soil

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

Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot \left(1+\sin(\phi)\right) + c \cdot \cos(\phi) = 11.3\ psi$$

Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + (c \cdot 0)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot 0 = 11.3\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$$p_{max} := u + p'_{max} = 18.8\ psi$$

Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

$h := 16.85\ ft$

Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 90\ pcf$

Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 10.5\ psi$

Minimum required mud pressure to overcome differntial head

$Q_f := 200\ gpm$

Assumed mud flow rate

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

Assumed yield point of mud per 100 square feet

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

Assumed plastic viscosity of mud

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

Computed mud flow velocity

$L_{structure} := 550\ ft$ Length to sturcture

$$\left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2}\right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)}\right)\right) = 0.003\ \frac{psi}{ft}$$

Check mud pressure units

$$p_2 := L_{structure} \cdot \left(\left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2}\right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)}\right)\right)\right) = 1.6\ psi$$

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 12.2\ psi$ Minimum required mud pressure

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

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

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

$H_c := H_{max} = 27.3\ ft$ Depth of cover

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

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

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

$\gamma = 110\ pcf$ Unit weight of soil, assumed

Can't divide by 0 ~ assume k goes to 1 (ie full soil column height)

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

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

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 9\ psi \qquad P_E = 1299\ psf$ Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

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

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

$\Delta y_{ELD\_short} := \frac{0.0125 \cdot P_E}{k_{short}} = 1.2\%$ Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437, PPI Handbook)

D1.3 Earth Load Deflection (Long Term)

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

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

$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 2.5\%$ Pipe deflection to diameter as per PPI Equ. 10 (Chp 12, p 437)

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

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

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

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

$\gamma_m = 90\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

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

$$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.1\%$$

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

D2.1 Buoyant Deflection (Long Term)

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

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

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

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

D4.1 - Net Short Term

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

Percent ring deflection in short term analysis

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

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 2.5\%$

Percent ring deflection in long term analysis (50 years)

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

D5 - Unconstrained Ring Buckling

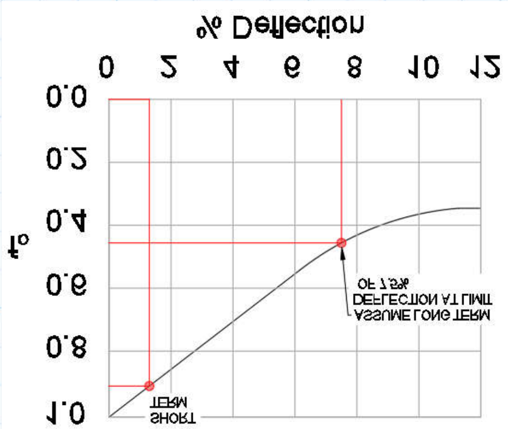
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

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

$N := 2.0$ — Factor of Safety

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

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



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

$f_{o\_short} := 0.92$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1 - \mu_{short}^{2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_short}}{N} = 117.7\ psi$$

Allowable unconstrained buckling pressure

$H = 16.8\ ft$ — Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 10.5\ psi$ — Pressure of drilling slurry

$P_{net} := P_{mud} = 10.5\ psi$ — Net external loading with open borehole

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

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

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

$N := 2.0$ — Factor of Safety

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

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

$f_{o\_long} := 0.45$ — Ovality compensation factor, Figure 3 (PPI Chp. 12). Use deflection limit calculated in Section D4.2

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

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 7.54 \ psi$ — Groundwater head pressure

$P_{net} := P_{GW}$ — Net external loading with open borehole

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

References

1. ASTM F 1962 -05 Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings
2. ASTM F 1804-08 Standard Practice for Determining Allowable Tensile Load for Polyethylene (PE) Gas Pipe During Pull-In Installation
3. Proposed Soil Properties for CHPE Package 1 HDDs, Kiewit, October 12, 2022.
4. Handbook of Polyethylete Pipe, 2008, Plastics Pipe Institute (PPI), Second Edition
5. Larry Slavin, 2009, Guidelines for Use of Mini-Horizontal Direction Drilling for Placement of High Density Polyethylene Pipe
6. Mohammad Najafi, 2013, Trenchless Technology, First Edition, McGraw Hill

93.A

Defining Parameters of Horizontal Directional Drilling :

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

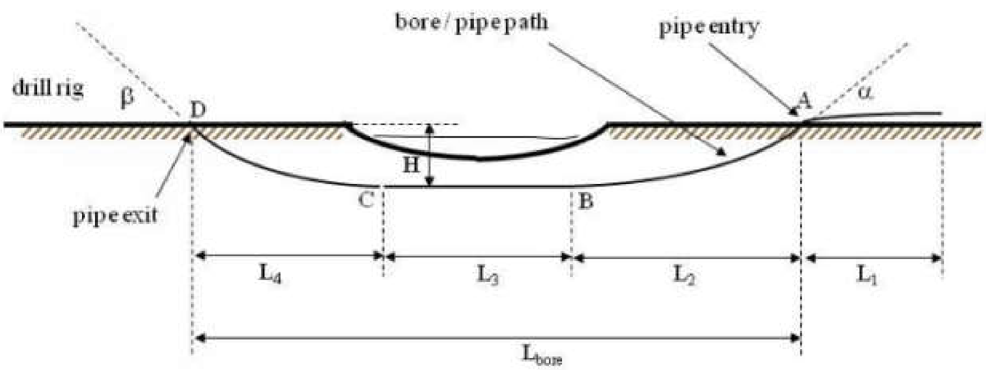


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 10\ °$ $\alpha_{in} := \alpha = 0.1745\ rad$	Borehole entry angle (degrees, radians)
$\beta := 14\ °$ $\beta_{exit} := \beta = 0.2443\ rad$	Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$	Final reamed bore diameter
$H_{max} := 44.7\ ft$	Max depth of bore hole to final reamed bore diameter
$H_{max1} := H_{max} + \frac{D_r}{2} = 45.45\ ft$	Max depth to bore hole springline from ground surface
$L_{total} := 744.0\ ft$	Total length of HDD crossing
$L_1 := 150\ ft$	Assumed pipe drag on surface, See Illustration 1
$L_2 := 370.1\ ft$	Horizontal length to achieve depth - provided by Contractor, See Illustration 1
$L_3 := 70.6\ ft$	Straight horizontal section
$L_4 := 296.5\ ft$	Horizontal distance to rise to surface, See Illustration 1
$H := 44.3\ ft$	Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1

$v_a := 0.1$ Friction coefficient before pipe enters (rollers assumed)

$v_b := 0.3$ Friction coefficient for the bundle within borehole (lubrication assumed)

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

$\gamma_a := 0.965$ Specific gravity of pipe

$\gamma_m := 80\ pcf$ Assumed unit weight of slurry

$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.3$ Specific gravity of slurry, assumed unit weight

$\gamma_c := 1.0$ Specific gravity of water to fill the pipe

$\Delta P := 10\ psi$ Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)

$g := 32.2\ \frac{ft}{s^2}$ Gravitational Constant

A - Axial Bending Stress:

$R_{avg.\_in} := 1000\ ft$ Radius of curvature at the entry, provided by Contractor

$R_{avg.\_out} := 1000\ ft$ Radius of curvature at the exit, provided by Contractor

$R := \frac{R_{avg.\_in} + R_{avg.\_out}}{2} = 1000\ ft$ Average radius of curvature at entry

$r_{rod} := 1200 \cdot D_{rod} = 350\ ft$ ASTM F 1962-99, Equation 1, p7

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

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

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

$e_a := \frac{D_1}{2 \cdot R} = 0.0004$ Strain within the casing pipe

$E_{12hr} := 57500 \cdot psi$ Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)

$S_a := e_a \cdot E_{12hr} = 25.8\ psi$ Axial bending stress within the casing pipe

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

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

B1.2 - Upward Buoyant Force: Effective weight

$$w_b := \left(\frac{\pi \cdot \left(D_1^2 + D_2^2\right)}{4}\right) \rho_w \cdot \gamma_b - w_a = 44.6\ plf$$ Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

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

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 748\ lbf$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}}\left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 7778\ lbf$$

Pullback force increase with depth

B1.6 - Pullback Force Point C:

$$T_c := T_b + \left(v_b \cdot w_b \cdot L_3\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 8660\ lbf$$

B1.7 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_c + v_b \cdot \left|w_b\right| \cdot L_4 - w_b \cdot H_{max} - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 11168\ lbf$$

B1.8 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_c, T_d\right) + \Delta T = 11965\ lbf$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi \cdot D_1^2\right)}{4}\right) \cdot \rho_w \cdot \left(\gamma_b - \gamma_c \cdot \left(1 - \left(\frac{2}{DR_1}\right)\right)^2\right) - w_a = 18.3\ plf$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 748\ lbf$$ Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 4128\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C:

$$T_{cfilled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_3\right) - e^{(v_b \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 4453\ lbf$$

B2.5 - Pullback Force at D:

$$T_{dfilled} := e^{(v_b \cdot \beta_{exit})} \cdot \left(T_{cfilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{(v_a \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{(v_a \cdot \alpha_{in})}\right)\right) = 6274\ lbf$$

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

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{cfilled}, T_{dfilled}\right) = 6274\ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

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

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

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 11500\ lbf$$ Pullback forces acting on Pipe 1 (Empty)

$$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 464\ lbf$$ Pullback forces acting on Pipe 2 (Empty)

$$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 6031\ lbf$$ Pullback forces acting on Pipe 1 (Ballast)

$$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 243\ lbf$$ Pullback forces acting on Pipe 2 (Ballast)

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

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

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

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

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

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

-Assume soil conditions of soft clay (CL), B202.1-1 does not extend to bottom tangent of HDD alginment.

- Diameter/radius based on the most critical stage (i.e. during pilot tube)

-Asssume cot(0 deg) = 0 theoretically infinite)

$D_{PT} := 5\ in$	Pilot tube diameter
$D_0 := 9.5\ in$	Initial borehole diameter for pilot tube
$H_w := 26.1 \cdot ft$	Depth of the bore below groundwater elevation
$H_c := 26.1\ ft$	Vertical separation distance between critical structure and pipe (Stream, ~2+25)
$\gamma := 110\ pcf$	Assumed unit weight soft clay
$\gamma_w := 62.4\ pcf$	Unit weight of water
$\gamma' := \gamma - \gamma_w = 47.6\ pcf$	Effective unit weight
$u := \gamma_w \cdot H_w = 11\ psi$	Initial pore water pressure
$\phi := 0\ deg$	Assumed friction Angle
$c := 800\ psf = 5.56\ psi$	Assumed cohesion of encountered material
$R_0 := \frac{D_{rod}}{2} = 1.75\ in$	Initial radius of the borehole
$R_{pmax} := \frac{1}{2} \cdot H_c = 13\ ft$	Radius of plastic zone (H/2 in clays & 2/3 H in sands)
$\sigma'_0 := \left(\left(\gamma \cdot \left(H_c - H_w\right)\right) + \gamma' \cdot H_w\right) = 9\ psi$	Initial effective stress

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

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

$$E_s := 15\ \frac{N}{mm^2} = 2176\ psi$$

Assumed modulus of elasticity

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

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

$\nu_s := 0.4$

Poissions ratio of material encountered

$$G := \frac{E_s}{2\left(1+\nu_s\right)} = 777\ psi$$

Shear modulus of soil

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

Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot (1+\sin(\phi)) + c \cdot \cos(\phi) = 14.2\ psi$$

Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + (c \cdot 0)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot 0 = 14.2\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$$p_{max} := u + p'_{max} = 25.5\ psi$$

Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

$h := 41.4\ ft$

Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 80\ pcf$

Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 23\ psi$

Minimum required mud pressure to overcome differntial head

$Q_f := 200\ gpm$

Assumed mud flow rate

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

Assumed yield point of mud per 100 square feet

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

Assumed plastic viscosity of mud

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

Computed mud flow velocity

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

$$\left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2}\right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)}\right)\right) = 0.003\ \frac{psi}{ft}$$

Check mud pressure units

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

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 23.7\ psi$ — Minimum required mud pressure

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

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

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

$H_c := H_{max} = 44.7\ ft$ — Depth of cover

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

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

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

$\gamma = 110\ pcf$ — Unit weight of soil, assumed

Can't divide by 0 ~ assume k goes to 1 (ie full soil column height)

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

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

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 15\ psi \quad P_E = 2128\ psf$ — Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

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

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

Variable in earth load deflection equation

$$\Delta y_{ELD\_short} := \frac{0.0125 \cdot P_E}{k_{short}} = 2.0\%$$

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

D1.3 Earth Load Deflection (Long Term)

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

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

Variable in earth load deflection equation

$$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 4.0\%$$

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

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

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

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

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

$\gamma_m = 80\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

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

$$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.1\%$$

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

D2.1 Buoyant Deflection (Long Term)

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

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

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

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

D4.1 - Net Short Term

$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 2.0\%$

Percent ring deflection in short term analysis

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

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 4.0\%$

Percent ring deflection in long term analysis (50 years)

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

D5 - Unconstrained Ring Buckling

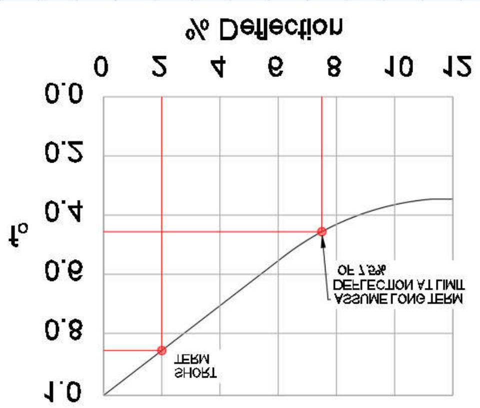
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

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

$N := 2.0$ — Factor of Safety

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

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



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

$f_{o\_short} := 0.87$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1 - \mu_{short}^{2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_short}}{N} = 111.3\ psi$$

Allowable unconstrained buckling pressure

$H = 44.3\ ft$ — Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 24.61\ psi$ — Pressure of drilling slurry

$P_{net} := P_{mud} = 24.61\ psi$ — Net external loading with open borehole

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

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

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

$N := 2.0$ — Factor of Safety

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

$E_{long} = 28200\ psi$

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

$f_{o\_long} := 0.45$

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

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

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 11.31\ psi$

Groundwater head pressure

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

Net external loading with open borehole

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

References

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

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

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

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

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

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

Defining Parameters of Horizontal Directional Drilling :

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

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

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

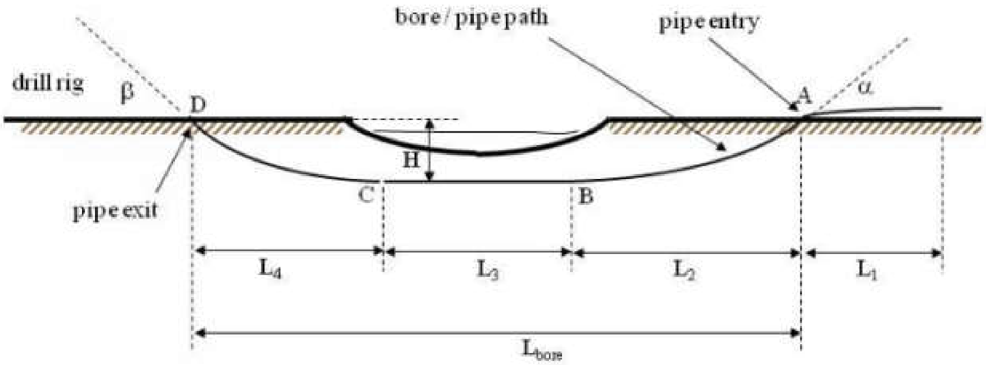


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 8\ °$ $\alpha_{in} := \alpha = 0.1396\ rad$ — Borehole entry angle (degrees, radians)
$\beta := 10\ °$ $\beta_{exit} := \beta = 0.1745\ rad$ — Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$ — Final reamed bore diameter
$H_{max} := 43.3\ ft$ — Max depth of bore hole to final reamed bore diameter

$H_{max1} := H_{max} + \frac{D_r}{2} = 44.05\ ft$ — Max depth to bore hole springline from ground surface

$L_{total} := 1176.5\ ft$ — Total length of HDD crossing
$L_1 := 150\ ft$ — Assumed pipe drag on surface, See Illustration 1

$L_2 := 234.6\ ft$ — Horizontal length to achieve depth - provided by Contractor, See Illustration 1

$L_{3\_1} := 174.6\ ft$ — Straight horizontal section, before curve

$L_{3\_2} := 32.9\ ft$ — Curve Length

$L_{3\_3} := 127.9\ ft$ — Straight horizontal section, after curve

$L_4 := 285.9\ ft$	Horizontal distance to rise to surface, See Illustration 1
$H := 32\ ft$	Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1
$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 90\ pcf$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.4$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

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

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

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

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

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

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

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

Effective weight

B1.2 - Upward Buoyant Force:

$$w_b := \left(\frac{\pi \cdot \left(D_1^{\,2} + D_2^{\,2}\right)}{4}\right) \rho_w \cdot \gamma_b - w_a = 51.2\ plf$$

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

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

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_{3\_1} + L_{3\_2} + L_{3\_3} + L_4\right)\right) = 845\ lbf$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}} \left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 6746\ lbf$$

Pullback force increase with depth

B1.6 - Pullback Force Point C1:

$$T_{c\_1} := T_b + \left(v_b \cdot w_b \cdot L_{3\_1}\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 9276\ lbf$$

B1.7 - Pullback Force Point C2:

$$\alpha_{curve} := 18.9\ °$$

$$T_{c\_2} := e^{v_b \cdot \alpha_{curve}} \left(T_{c\_1} + v_b \cdot \left|w_b\right| \cdot L_{3\_2} + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_{3\_2} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 13215\ lbf$$

B1.8 - Pullback Force Point C3:

$$T_{c\_3} := T_{c\_2} + \left(v_b \cdot w_b \cdot L_{3\_3}\right) - e^{\left(v_b \cdot \alpha_{curve}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_3} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 15059\ lbf$$

B1.9 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{c\_3} + v_b \cdot \left|w_b\right| \cdot L_4 - w_b \cdot H_{max} - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 17904\ lbf$$

B1.10 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_{c\_1}, T_{c\_2}, T_{c\_3}, T_d\right) + \Delta T = 18700\ lbf$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi \cdot D_1^{\,2}\right)}{4}\right) \cdot \rho_w \cdot \left(\gamma_b - \gamma_c \cdot \left(1 - \left(\frac{2}{DR_1}\right)\right)^2\right) - w_a = 24.6\ plf$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_{3\_1} + L_{3\_2} + L_{3\_3} + L_4\right)\right) = 845\ lbf$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 4009\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C1:

$$T_{c1\_filled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_1}\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 5147\ lbf$$

B2.5 - Pullback Force Point C2:

$\alpha_{curve} = 18.9\ °$

$$T_{c2\_filled} := e^{v_b \cdot \alpha_{curve}} \left(T_{c1\_filled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_2} + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_{3\_2} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 7160\ lbf$$

B2.6 - Pullback Force Point C3:

$$T_{c3\_filled} := T_{c2\_filled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_3}\right) - e^{\left(v_b \cdot \alpha_{curve}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 7941\ lbf$$

B2.7 - Pullback Force at D:

$$T_{dfilled} := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{c3\_filled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 10338\ lbf$$

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

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{c1\_filled}, T_{c2\_filled}, T_{c3\_filled}, T_{dfilled}\right) = 10338\ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

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

Cross-sectional area of Pipe 1

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

Cross-sectional area of Pipe 2

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 17975\ lbf$$

Pullback forces acting on Pipe 1 (Empty)

$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 726\ lbf$ Pullback forces acting on Pipe 2 (Empty)

$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 9937\ lbf$ Pullback forces acting on Pipe 1 (Ballast)

$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 401\ lbf$ Pullback forces acting on Pipe 2 (Ballast)

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

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

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

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

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

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

- Geologic conditions through alignment will vary from very poor (inferred from weathered rock) to fair rock mass quality based on Boring K204.2. Assume critical section is silty sand based on boring K-203.5 & -.6 for Mathcad.

$H_w := 16.5 \cdot ft$ Depth of the bore below groundwater elevation

$H_c := 27\ ft$ Vertical separation distance between critical structure and pipe (Main St)

$\gamma := 125\ pcf$ Assumed unit weight silty sand (SM)

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

$\gamma' := \gamma - \gamma_w = 62.6\ pcf$ Effective unit weight

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

$\phi := 34\ deg$ Assumed friction Angle

$c := 0\ psf = 0\ psi$ Assumed cohesion of encountered material

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

$R_{pmax} := \frac{2}{3} \cdot H_c = 18\ ft$ Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := \left(\left(\gamma \cdot \left(H_c - H_w\right)\right) + \gamma' \cdot H_w\right) = 16\ psi$ Initial effective stress

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

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

$E_s := 7\ \frac{N}{mm^2} = 1015\ psi$

Assumed modulus of elasticity

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

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

$\nu_s := 0.25$

Poissions ratio of material encountered

$G := \dfrac{E_s}{2\left(1+\nu_s\right)} = 406\ psi$ Shear modulus of soil

$Q := \dfrac{\left(\sigma'_0 \cdot \sin(\phi)\right) + \left(c \cdot \cot(\phi)\right)}{G} = 0.0224$

Coefficient of Delft Equation

$p'_f := \sigma'_0 \cdot \left(1+\sin(\phi)\right) + c \cdot \cos(\phi) = 25.4\ psi$

Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + \left(c \cdot \cot(\phi)\right)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot \cot(\phi) = 99\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$p_{max} := u + p'_{max} = 106.2\ psi$ Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

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

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

$h := 23.18\ ft$ Elevation difference between level of bore hole front and exit point of mud flow

$\gamma_m = 90\ pcf$ Unit weight of slurry/mud

$p_1 := \gamma_m \cdot h = 14.5\ psi$ Minimum required mud pressure to overcome differntial head

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

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

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

$D_{eff} := 13.4870\ in$ Effective diameter of bundle

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

Computed mud flow velocity

$$L_{total} := 1176.5\ ft$$

Total length of HDD crossing

$$p_2 := L_{total} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_r - \left(D_{eff}\right)\right)^2}\right) + \left(\frac{\tau_o}{\left(D_r - \left(D_{eff}\right)\right)}\right)\right) = 3.5\ psi$$

Minimum required mud pressure to create flow inside the borehole

$$p_{min.} := p_1 + p_2 = 18\ psi$$

Minimum required mud pressure

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

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

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

$H_c := H_{max} = 43.3\ ft$ — Depth of cover

$\phi = 34\ deg$ — Friction angle of soil

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

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

$\gamma = 125\ pcf$ — Unit weight of soil, assumed

$$k := \frac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)\right)}{2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)} = 0.073$$

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

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 1\ psi \quad P_E = 199\ psf$ — Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

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

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

Variable in earth load deflection equation

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

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

D1.3 Earth Load Deflection (Long Term)

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

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

Variable in earth load deflection equation

$$\Delta y_{ELD\_long} := \frac{0.0125 \cdot P_E}{k} = 0.4\%$$

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

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

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

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

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

$\gamma_m = 90\ pcf$ — Assumed unit weight of fluid in borehole (Slurry unit weight)

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

$$\Delta y_{bouyant} := \frac{0.1169 \cdot \gamma_m \cdot \left(\frac{D_1}{2}\right)^4}{E_{short} \cdot I} = 0.1\%$$

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

D2.1 Buoyant Deflection (Long Term)

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

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

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

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

D4.1 - Net Short Term

$\Delta y_{short\_net} := \Delta y_{ELD\_short} + \Delta y_{bouyant} + \Delta y_{R\_short} = 0.2\%$

Percent ring deflection in short term analysis

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

D4.2 - Net Long Term

$\Delta y_{long\_net} := \Delta y_{ELD\_long} + \Delta y_{R\_long} = 0.4\%$

Percent ring deflection in long term analysis (50 years)

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

D5 - Unconstrained Ring Buckling

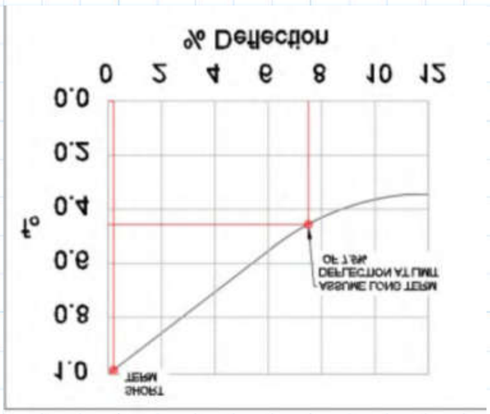
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

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

$N := 2.0$ Factor of Safety

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

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



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

$f_{o\_short} := 0.98$

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

Allowable unconstrained buckling pressure

$H = 32\ ft$ Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 20\ psi$ Pressure of drilling slurry

$P_{net} := P_{mud} = 20\ psi$ Net external loading with open borehole

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

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

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

$N := 2.0$ Factor of Safety

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

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

$f_{o\_long} := 0.45$ — Ovality compensation factor, Figure 3 (PPI Chp. 12). Use deflection limit calculated in Section D4.2

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

Allowable unconstrained buckling pressure

$P_{GW} := \gamma_w \cdot H_w = 7.15\ psi$ — Groundwater head pressure

$P_{net} := P_{GW}$ — Net external loading with open borehole

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

References

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

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

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

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

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

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

Defining Parameters of Horizontal Directional Drilling :

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

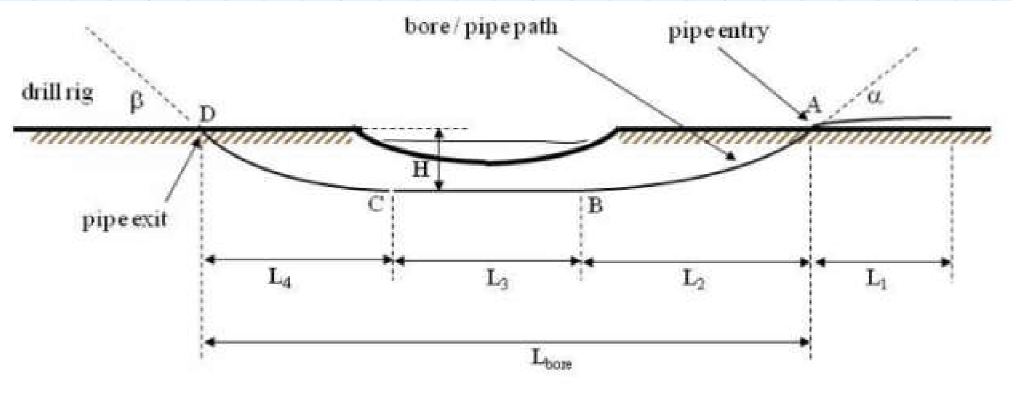


Illustration 1 - Schematic of Drive Cross-section

$\alpha := 10\ °$ $\alpha_{in} := \alpha = 0.1745\ rad$	Borehole entry angle (degrees, radians)
$\beta := 10\ °$ $\beta_{exit} := \beta = 0.1745\ rad$	Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$	Final reamed bore diameter
$H_{max} := 53\ ft$	Max depth of bore hole to final reamed bore diameter
$H_{max1} := H_{max} + \frac{D_r}{2} = 53.75\ ft$	Max depth to bore hole springline from ground surface
$L_{total} := 1241.4\ ft$	Total length of HDD crossing
$L_1 := 150\ ft$	Assumed pipe drag on surface, See Illustration 1
$L_2 := 472.6\ ft$	Horizontal length to achieve depth - provided by Contractor, See Illustration 1
$L_{3\_1} := 100\ ft$	Straight horizontal section, before curve
$L_{3\_2} := 144.7\ ft$	Curve Length
$L_{3\_3} := 164.5\ ft$	Straight horizontal section, after curve

$L_4 := 361.6\ ft$ — Horizontal distance to rise to surface, See Illustration 1

$H := 46\ ft$ — Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1

$v_a := 0.1$ — Friction coefficient before pipe enters (rollers assumed)

$v_b := 0.3$ — Friction coefficient for the bundle within borehole (lubrication assumed)

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

$\gamma_a := 0.965$ — Specific gravity of pipe

$\gamma_m := 70\ pcf$ — Assumed unit weight of slurry

$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.1$ — Specific gravity of slurry, assumed unit weight

$\gamma_c := 1.0$ — Specific gravity of water to fill the pipe

$\Delta P := 10\ psi$ — Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)

$g := 32.2\ \frac{ft}{s^2}$ — Gravitational Constant

A - Axial Bending Stress:

$R_{avg.\_in} := 1000\ ft$ — Radius of curvature at the entry, provided by Contractor

$R_{avg.\_out} := 1000\ ft$ — Radius of curvature at the exit, provided by Contractor

$R := \frac{R_{avg.\_in} + R_{avg.\_out}}{2} = 1000\ ft$ — Average radius of curvature at entry

$r_{rod} := 1200 \cdot D_{rod} = 350\ ft$ — ASTM F 1962-99, Equation 1, p7

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

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

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

$e_a := \frac{D_1}{2 \cdot R} = 0.0004$ — Strain within the casing pipe

$E_{12hr} := 57500 \cdot psi$ — Apparent modulus of elasticity for PE4710, Base Temperature of 73 deg. Fahrenheit at 10 hrs of sustained loading (Table X1.1 ASTM F 1962)

$S_a := e_a \cdot E_{12hr} = 25.8\ psi$ — Axial bending stress within the casing pipe

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

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

Effective weight

B1.2 - Upward Buoyant Force:

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

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

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

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_{3\_1} + L_{3\_2} + L_{3\_3} + L_4\right)\right) = 1175\ \boldsymbol{lbf}$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}}\left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 8615\ \boldsymbol{lbf}$$

Pullback force increase with depth

B1.6 - Pullback Force Point C1:

$$T_{c\_1} := T_b + \left(v_b \cdot w_b \cdot L_{3\_1}\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 9666\ \boldsymbol{lbf}$$

B1.7 - Pullback Force Point C2:

$$\alpha_{curve} := 8.18\ °$$

$$T_{c\_2} := e^{v_b \cdot \alpha_{curve}}\left(T_{c\_1} + v_b \cdot \left|w_b\right| \cdot L_{3\_2} + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_{3\_2} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 13784\ \boldsymbol{lbf}$$

B1.8 - Pullback Force Point C3:

$$T_{c\_3} := T_{c\_2} + \left(v_b \cdot w_b \cdot L_{3\_3}\right) - e^{\left(v_b \cdot \alpha_{curve}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_3} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 15515\ \boldsymbol{lbf}$$

B1.9 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{c\_3} + v_b \cdot \left|w_b\right| \cdot L_4 - w_b \cdot H_{max} - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 18243\ \boldsymbol{lbf}$$

B1.10 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_{c\_1}, T_{c\_2}, T_{c\_3}, T_d\right) + \Delta T = 19039\ \boldsymbol{lbf}$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

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

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_{3\_1} + L_{3\_2} + L_{3\_3} + L_4\right)\right) = 1175\ lbf$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 4130\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C1:

$$T_{c1\_filled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_1}\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 4402\ lbf$$

B2.5 - Pullback Force Point C2:

$$\alpha_{curve} = 8.18\ °$$

$$T_{c2\_filled} := e^{v_b \cdot \alpha_{curve}} \left(T_{c1\_filled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_2} + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_{3\_2} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 5933\ lbf$$

B2.6 - Pullback Force Point C3:

$$T_{c3\_filled} := T_{c2\_filled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_{3\_3}\right) - e^{\left(v_b \cdot \alpha_{curve}\right)} \cdot \left(v_a \cdot w_a \cdot L_{3\_1} \cdot e^{\left(v_a \cdot \alpha_{curve}\right)}\right) = 6440\ lbf$$

B2.7 - Pullback Force at D:

$$T_{dfilled} := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_{c3\_filled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 7835\ lbf$$

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

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{c1\_filled}, T_{c2\_filled}, T_{c3\_filled}, T_{dfilled}\right) = 7835\ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

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

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

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 18300\ lbf$$ Pullback forces acting on Pipe 1 (Empty)

$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 739\ lbf$ Pullback forces acting on Pipe 2 (Empty)

$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 7531\ lbf$ Pullback forces acting on Pipe 1 (Ballast)

$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 304\ lbf$ Pullback forces acting on Pipe 2 (Ballast)

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

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

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

C - Allowable Mud Pressures:

C1 - Max. Allowable Driling Fluid Pressure

Assumptions:

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

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

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

$H_c := 25.0\ ft$ — Vertical separation distance between critical structure and pipe (Coyemans Creek)

$\gamma := 140\ pcf$ — Assumed unit weight shale bedrock

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

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

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

$\phi := 37\ deg$ — Assumed friction Angle

$c := 0\ psf = 0\ psi$ — Assumed cohesion of encountered material

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

$R_{pmax} := \frac{2}{3} \cdot H_c = 17\ ft$ — Radius of plastic zone (H/2 in clays & 2/3 H in sands)

$\sigma'_0 := ((\gamma \cdot (H_c - H_w)) + \gamma' \cdot H_w) = 24\ psi$ — Initial effective stress

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

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

$E_s := 4000\ psi$

Assumed modulus of elasticity

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

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

$\nu_s := 0.4$

Poissions ratio of material encountered

$$G := \frac{E_s}{2\left(1+\nu_s\right)} = 1429\ psi$$

Shear modulus of soil

$$Q := \frac{\left(\sigma'_0 \cdot \sin(\phi)\right) + \left(c \cdot \cot(\phi)\right)}{G} = 0.0102$$

Coefficient of Delft Equation

$$p'_f := \sigma'_0 \cdot \left(1+\sin(\phi)\right) + c \cdot \cos(\phi) = 38.9\ psi$$

Mud pressure at which the first plastic deformation takes place

$$p'_{max} := \left(p'_f + \left(c \cdot \cot(\phi)\right)\right) \cdot \left(\left(\left(\frac{R_0}{R_{pmax}}\right)^2 + Q\right)^{\left(\frac{-\sin(\phi)}{1+\sin(\phi)}\right)}\right) - c \cdot \cot(\phi) = 217.1\ psi$$

Maximum allowable effective mud pressure (Delft Equation)

$$p_{max} := u + p'_{max} = 217.1\ psi$$

Maximum allowable mud pressure

C2 -Min. Allowable Drilling Fluid Pressure

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

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

$h := 48.85\ ft$ — Elevation difference between level of bore hole front and exit point of mud flow

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

$p_1 := \gamma_m \cdot h = 23.7\ psi$ — Minimum required mud pressure to overcome differntial head

$Q_f := 80\ gpm$ — Assumed mud flow rate

$\tau_o := 25\ \frac{lbf}{100 \cdot ft^2}$ — Assumed yield point of mud per 100 square feet

$\mu_{pl} := 72 \cdot \frac{poise}{100}$ — Assumed plastic viscosity of mud

$D_{eff} := 13.4870\ in$ — Effective diameter of bundle

$$v := \frac{Q_f}{0.785\left(\left(D_0^2 - D_{PT}^2\right)\right)} = 30.1\ \frac{ft}{min}$$

Computed mud flow velocity

$L_{total} = 1241.4\ ft$ Length of bore

$$p_2 := L_{total} \cdot \left(\left(\frac{\mu_{pl} \cdot v}{\left(D_0 - D_{PT}\right)^2} \right) + \left(\frac{\tau_o}{\left(D_0 - D_{PT}\right)} \right) \right) = 5.8\ psi$$

Minimum required mud pressure to create flow inside the borehole

$p_{min.} := p_1 + p_2 = 29.5\ psi$ Minimum required mud pressure

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

D - Pipe Structural Capacities:

D1- Ring Deflection (Short & Long Term):

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

$H_c := H_{max} = 53\ ft$ — Depth of cover

$\phi = 37\ deg$ — Friction angle of soil

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

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

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

$$k := \frac{1 - \exp\left(-2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)\right)}{2 \cdot \frac{K \cdot H_c}{B} \cdot \tan\left(\frac{\phi}{2}\right)} = 0.061$$

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

$P_E := k \cdot (\gamma - \gamma_w) \cdot (H_c) = 2\ psi \qquad P_E = 250\ psf$ — Effective overburden pressure

D1.2 Earth Load Deflection (Short Term)

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

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

Variable in earth load deflection equation

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

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

D1.3 Earth Load Deflection (Long Term)

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

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

Variable in earth load deflection equation

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

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

D2 - Buoyant Deflection

D2.1 Buoyant Deflection (Short Term)

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

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

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

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

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

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

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

D2.1 Buoyant Deflection (Long Term)

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

D3 - Reissner Effect Deflection (Short Term)

D3.1 - Reissner Effect Deflection (Short Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect

D3.2 - Reissner Effect Deflection (Long Term)

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

$R = 1000\ ft$ — Radius of curvature

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

Deflection due to longitudinal bending

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

Pipe ring deflection due to the Reisnner Effect, long term

D4 - Net Ring Deflection

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

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

D4.1 - Net Short Term

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

Percent ring deflection in short term analysis

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

D4.2 - Net Long Term

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

Percent ring deflection in long term analysis (50 years)

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

D5 - Unconstrained Ring Buckling

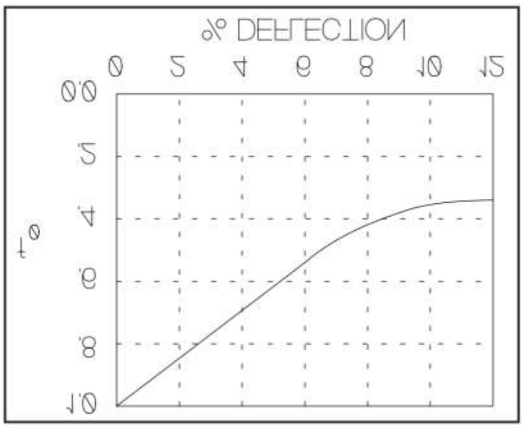
D5.1 - Unconstrained Ring Buckling, Levy's Equation (Short Term-During Pull)

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

$N := 2.0$ Factor of Safety

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

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



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

$f_{o\_short} := 0.99$

$$P_{UC\_short} := \left(\frac{2 \cdot E_{short}}{1 - \mu_{short}^{2}}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^{3} \cdot \frac{f_{o\_short}}{N} = 126.7\ psi$$

Allowable unconstrained buckling pressure

$H = 46\ ft$ Elevation difference between the lowest point in borehole and entry or exit pit

$P_{mud} := \gamma_m \cdot H = 22.36\ psi$ Pressure of drilling slurry

$P_{net} := P_{mud} = 22.36\ psi$ Net external loading with open borehole

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

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

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

$N := 2.0$ Factor of Safety

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

$E_{long} = 28200\ psi$

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

$f_{o\_long} := 0.9$

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

$$P_{UC\_long} := \left(\frac{2 \cdot E_{long}}{1 - {\mu_{long}}^2}\right) \cdot \left(\frac{1}{DR_1 - 1}\right)^3 \cdot \frac{f_{o\_long}}{N} = 62.2\ psi$$

Allowable unconstrained buckling pressure

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

Groundwater head pressure

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

Net external loading with open borehole

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

References

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

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

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

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

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

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

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Defining Parameters of Horizontal Directional Drilling :

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

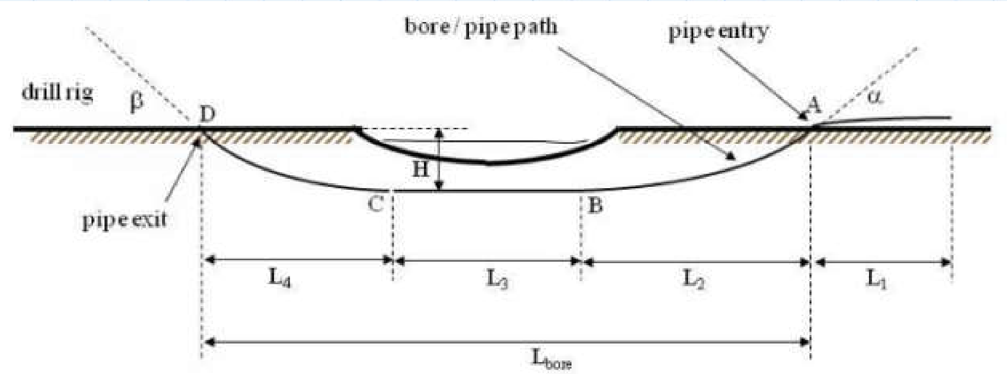

Illustration 1 - Schematic of Drive Cross-section

$\alpha := 12\ °$ $\quad \alpha_{in} := \alpha = 0.2094\ rad$	Borehole entry angle (degrees, radians)
$\beta := 8\ °$ $\quad \beta_{exit} := \beta = 0.1396\ rad$	Borehole exit angle (degrees, radians)
$D_r := 18 \cdot in$	Final reamed bore diameter
$H_{max} := 79.8\ ft$	Max depth of bore hole to final reamed bore diameter
$H_{max1} := H_{max} + \frac{D_r}{2} = 80.55\ ft$	Max depth to bore hole springline from ground surface
$L_{total} := 2124.6\ ft$	Total length of HDD crossing
$L_1 := 150\ ft$	Assumed pipe drag on surface, See Illustration 1
$L_2 := 208.2\ ft$	Horizontal length to achieve depth - provided by Contractor, See Illustration 1
$L_3 := 1609\ ft$	Straight horizontal section
$L_4 := 307.4\ ft$	Horizontal distance to rise to surface, See Illustration 1
$H := 16.8\ ft$	Elevation difference between the lowest point in borehole and slurry pump elevation (entry or exit pit), See Illustration 1

$v_a := 0.1$	Friction coefficient before pipe enters (rollers assumed)
$v_b := 0.3$	Friction coefficient for the bundle within borehole (lubrication assumed)
$\rho_w := 62.4\ pcf$	Unit weight of water
$\gamma_a := 0.965$	Specific gravity of pipe
$\gamma_m := 90\ pcf$	Assumed unit weight of slurry
$\gamma_b := \frac{\gamma_m}{\rho_w} = 1.4$	Specific gravity of slurry, assumed unit weight
$\gamma_c := 1.0$	Specific gravity of water to fill the pipe
$\Delta P := 10\ psi$	Hydrokinetic Pressure (p. 443, Ch12 PPI Handbook)
$g := 32.2\ \frac{ft}{s^2}$	Gravitational Constant

A - Axial Bending Stress:

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

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

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

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

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

B - Site Specific Analyses: Pullback Force:

B1 - Empty Pipe

B1.1 - Effective Weight of Empty Pipe:

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

Effective weight

B1.2 - Upward Buoyant Force:

$$w_b := \left(\frac{\pi \cdot \left(D_1^{\,2} + D_2^{\,2}\right)}{4}\right) \rho_w \cdot \gamma_b - w_a = 51.2\ \mathbf{plf}$$

Upward buoyant force of empty pipe

B1.3 - Hydrokinetic Pressure:

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

Hydrokinetic force

B1.4 - Pullback Force Point A:

$$T_a := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 1925\ \mathbf{lbf}$$

Pullback force when pipe enters the ground

B1.5 - Pullback Force Point B:

$$T_b := e^{v_b \cdot \alpha_{in}} \left(T_a + v_b \cdot \left|w_b\right| \cdot L_2 + w_b \cdot H_{max} - v_a \cdot w_a \cdot L_2 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 9619\ \mathbf{lbf}$$

Pullback force increase with depth

B1.6 - Pullback Force Point C:

$$T_c := T_b + \left(v_b \cdot w_b \cdot L_3\right) - e^{\left(v_b \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right) = 32888\ \mathbf{lbf}$$

B1.7 - Pullback Force at D:

$$T_d := e^{\left(v_b \cdot \beta_{exit}\right)} \cdot \left(T_c + v_b \cdot \left|w_b\right| \cdot L_4 - w_b \cdot H_{max} - e^{\left(v_a \cdot \alpha_{in}\right)} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{\left(v_a \cdot \alpha_{in}\right)}\right)\right) = 34681\ \mathbf{lbf}$$

B1.8 - Maximum Pullback Force - Empty Pipe:

$$P_{max\_empty} := \max\left(T_a, T_b, T_c, T_d\right) + \Delta T = 35477\ \mathbf{lbf}$$

Maximum Pullback Force

B2 - Filled Pipe with Water

B2.1 - Upward Buoyant Force:

$$w_{bfilled} := \left(\frac{\left(\pi \cdot D_1^{\,2}\right)}{4}\right) \cdot \rho_w \cdot \left(\gamma_b - \gamma_c \cdot \left(1 - \left(\frac{2}{DR_1}\right)\right)^2\right) - w_a = 24.6\ \mathbf{plf}$$

Upward buoyant force of pipe filled with water

B2.2 - Pullback Force Point A:

$$T_{afilled} := e^{v_a \cdot \alpha_{in}} \cdot \left(v_a \cdot w_a \cdot \left(L_1 + L_2 + L_3 + L_4\right)\right) = 1925\ \mathbf{lbf}$$

Pullback force enter ground

B2.3 - Pullback Force Point B:

$$T_{bfilled} := e^{v_b \cdot \alpha_{in}} \left(T_{afilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_2 + w_{bfilled} \cdot H_{max} + v_a \cdot w_a \cdot L_2 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 5971\ lbf$$

Pullback force increase and decrease with depth

B2.4 - Pullback Force Point C:

$$T_{cfilled} := T_{bfilled} + \left(v_b \cdot \left|w_{bfilled}\right| \cdot L_3\right) - e^{(v_b \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_3 \cdot e^{(v_a \cdot \alpha_{in})}\right) = 16418\ lbf$$

B2.5 - Pullback Force at D:

$$T_{dfilled} := e^{(v_b \cdot \beta_{exit})} \cdot \left(T_{cfilled} + v_b \cdot \left|w_{bfilled}\right| \cdot L_4 - e^{(v_a \cdot \alpha_{in})} \cdot \left(v_a \cdot w_a \cdot L_4 \cdot e^{(v_a \cdot \alpha_{in})}\right)\right) = 19214\ lbf$$

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

$$P_{max} := \max\left(T_{afilled}, T_{bfilled}, T_{cfilled}, T_{dfilled}\right) = 19214\ lbf$$

Maximum Pullback Force

B3 - Safe Pull Strength / Ultimate Tensile Load Check:

B3.1 Safe Pullback Check

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

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

$$P_{11} := \frac{A_1 \cdot P_{max\_empty}}{A_1 + A_2} = 34101\ lbf$$ Pullback forces acting on Pipe 1 (Empty)

$$P_{21} := \frac{A_2 \cdot P_{max\_empty}}{A_1 + A_2} = 1376\ lbf$$ Pullback forces acting on Pipe 2 (Empty)

$$P_{12} := \frac{A_1 \cdot P_{max}}{A_1 + A_2} = 18468\ lbf$$ Pullback forces acting on Pipe 1 (Ballast)

$$P_{22} := \frac{A_2 \cdot P_{max}}{A_1 + A_2} = 745\ lbf$$ Pullback forces acting on Pipe 2 (Ballast)

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

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

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